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Standard/Handbook for RF Ionization Breakdown Prevention in Spacecraft Components

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Executive Summary

This document provides a standardized process for mitigation of radio frequency (RF) ionization breakdown (IB) within spacecraft components. As the companion to the multipactor document, Aerospace Report No. TOR-2014-02198, *Standard/Handbook for Radio Frequency Breakdown Prevention in Spacecraft Components*, this document expands the scope to include system engineering processes to prevent ionization breakdown. It is meant for component designers and satellite system engineers, as well as the customer community. It provides worst-case conditions, margin requirements, and state-of-the-art verification methods for those requirements. The recommended methods are provided to ensure proper requirement verification for all satellite and spacecraft RF components susceptible to ionization breakdown.

As RF component power levels increase, the processes and risk mitigation strategies described here increase in importance. Ionization breakdown can lead to catastrophic device damage and/or significant mission impact. As such, this document provides methodologies to minimize potential risks in applicable RF systems and components. Many RF breakdown-related issues can be traced to a lack of standard processes for analysis and test. The processes described in this document focus on identifying bounding, worst-case conditions for known system parameters and applying these conditions to a broad range of components and RF systems. This approach uses bounding case calculations and measurable/available data for the particular system and component under investigation. Worst-case conditions are combined with standard analysis and test processes to minimize device susceptibility to RF breakdown.

The document structure follows the typical component development process, starting with high-level component definitions and determination of worst-case system parameters. Subsequent sections continue the process by providing margin requirements and minimum verification requirements. These minimum verification requirements use state-of-the-art tools for both analysis and test, which are necessary to ensure proper hardware operation. Lastly, recommended analysis and test guidelines illustrate industry best practices and considerations for different component types.

Customer, contractor, and supplier groups will benefit from the clearly defined margin requirements. Proper implementation of the latest analysis techniques can, in some cases, eliminate the need for expensive qualification/acceptance testing with accurate and representative numerical analysis. Adherence to test requirements will provide risk reduction and early issue identification and prevent expensive failures late into the integration cycle.

This document details how ionization breakdown risk mitigation becomes possible through proper and careful analysis processes and test methods.

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1. Introduction

1.1 Purpose

This document provides a standard set of requirements and practices to prevent ionization breakdown (IB) failures in spacecraft components and systems. Ionization breakdown is a high-energy radio frequency (RF) discharge that can occur when the insulating media, often air, is no longer able to withstand the electric field between two conductors. This effect occurs when the electric field magnitude is strong enough to accelerate electrons to sufficient energies to cause ionization of neutral gas molecules. At high pressures, the mean free path between molecules is too short for electrons to gain sufficient energy to ionize neutral particles. At low pressures, there are too few neutral particles for ionization to occur at a high rate. In this way, plasma breakdown is driven by the balance between plasma generation due to ionization and losses due to physical electron diffusion out of the breakdown region and electron attachment. The two key parameters are electric field and gas pressure/density, and their relationship is described in Figure 1.1, which is commonly called a Paschen curve. The Paschen curve reaches a minimum at the critical pressure, which is the pressure at which a device is most susceptible to ionization breakdown. During an ionization breakdown, large amounts of energy can be discharged in a small volume, releasing large amounts of heat, melting local surfaces, and generating debris, all of which will likely damage or destroy the hardware. Details of the physics of ionization breakdown are presented in Appendix B.

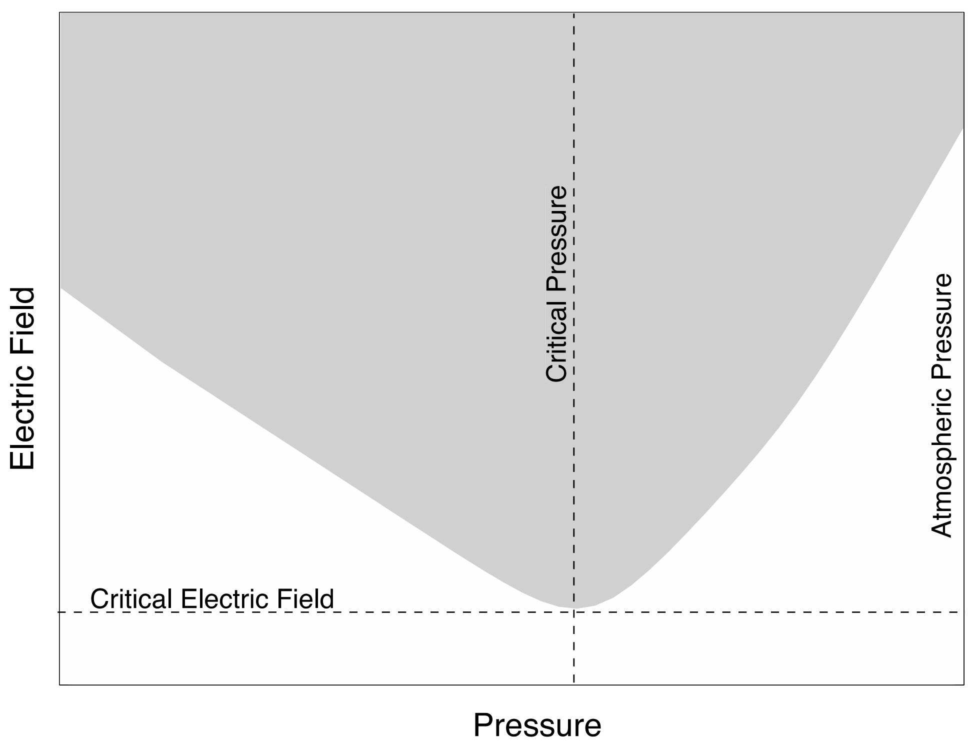


Figure 1.1. An example Paschen curve shows the relationship between electric field and pressure, and defines the region where ionization breakdown can occur.

This document provides minimum component verification requirements for analysis and test while taking into consideration the RF system configuration. Supporting documentation describes proper design,

analysis, and test guidelines. The document framework is based on defining worst-case parameters as inputs to analysis or test criteria for all components within the RF system.

With properly defined worst-case conditions, the document addresses required margins for analysis and test for three categories of devices. Subsequent sections provide minimum verification requirements to demonstrate the margin requirements for both analysis and test.

Handbook sections based on state-of-the-art industry best practices are also provided as guidelines to aid manufacturers and contractors. Typical approaches including examples for both analysis and test are provided. Incorporating this document and its improved process into the development and test cycles of an RF component will reduce the risks associated with RF breakdown failure. The document aims to reduce program risk and elevated cost of excessive margin requirements.

1.2 Document Applicability and Features

This document is intended for RF and microwave satellite and launch vehicle system and component manufacturers. It applies to RF components that operate at frequencies greater than 100 MHz at internal pressure greater than 10^{-4} Torr. Some features of this document include:

- A device categorization structure that helps tailor specific requirements for the device under consideration

- A system analysis process that provides the worst-case input power for each device under consideration. Parameters such as field enhancement due to voltage standing wave ratio (VSWR) can be accurately predicted or evaluated from the actual system hardware.

- Margin requirements for component-level analysis and test

- Minimum verification requirements for component-level test or analysis

- Recommended methodologies and best practices for component-level test and analysis

The words “device,” “component,” and “unit,” are used interchangeably throughout the document.

1.3 Document Tailoring

This document provides the framework for a low-risk process approach for preventing ionization breakdown. Specific tailoring of this document for different devices and/or systems may be considered by the customer or governing authority. The characteristics of the product, its system applications, and the rationale that reduces the performance risk shall be documented, reviewed, and approved by the governing authority prior to any requirement tailoring.

1.4 General Document Structure and Process Overview

The block diagram of a generalized RF system suitable for evaluation using this document is depicted in Figure 1.2. This simple example shows an RF amplifier driving N components. Such components may be connecting transmission lines, cable assemblies, filters, isolation devices, antenna, and other devices in the RF path. This document provides a process in which the applicable power for each component is determined, an appropriate margin is chosen for the device category, and analysis and test requirements are verified.

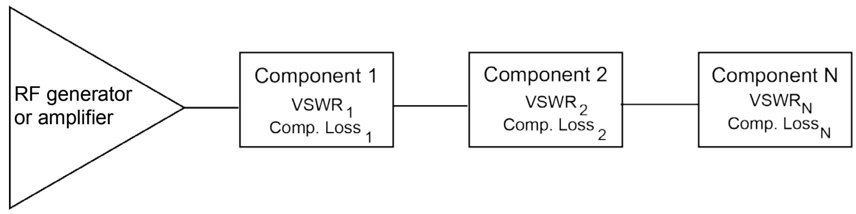


Figure 1.2. Simplified schematic of a high-power RF system that could be subject to ionization breakdown.

The goal is to determine realistic but worst-case electromagnetic fields that could be present in each susceptible component. Once many of the system parameters such as component losses and VSWR are known, these can be applied to the incident RF power. Once the worst-case RF power within a component is determined, an appropriate margin for the device class and verification method (analysis or test) can be applied to this worst-case condition.

Figure 1.3 illustrates the document structure and the overall process for IB mitigation. In general, each section provides foundational analysis and requirements that are used in the subsequent sections. The intent and process flow of each of the sections is summarized below.

- *Section 2: Minimum Ionization Breakdown Criteria*—Provides minimum criteria that determine under what conditions RF components are deemed susceptible to ionization breakdown.

- *Section 3: System Analysis Requirements*—Presents an analysis methodology that applies to the RF system as a whole (e.g., from the amplifier to the antenna). The goal of this section is to determine the worst-case but realistic power to each breakdown-susceptible component within the RF system using available data. The requirements and margins specified in section 4 require worst-case power to be defined for each component using this method.

- *Section 4: Margin Requirements*—Specifies the margin requirements for analysis and test to be applied to the worst-case component power level determined in section 3.

- *Section 5: Analysis Verification*—Provides a minimum set of analysis requirements to verify the margins provided in section 4. Different analysis methods are outlined for the different device categories defined in the section.

- *Section 6: Test Verification*—Provides a minimum set of test requirements to verify the margins provided in section 4. These requirements shall apply to all ionization breakdown tests for spacecraft components.

- *Section 7: Recommended Analysis Methodology*—Describes state-of-the-art and current best practices for analysis methods. It provides examples of analysis methods that can be implemented to meet the minimum requirements given in section 5.

- *Section 8: Recommended Test Methodology*—Describes state-of-the-art and current best practices for test methods. Section 8 provides additional guidance on ionization breakdown testing and examples to meet the requirements of section 6.

- *Appendix A: Hermetic Devices*—Provides definitions, test and qualification processes, margins, and analysis unique to hermetically sealed RF devices used in space systems.

- *Appendix B: Ionization Breakdown Background*

- *Appendix C: Comparison of Analytical Curves and Test Data*
- *Appendix D: References*

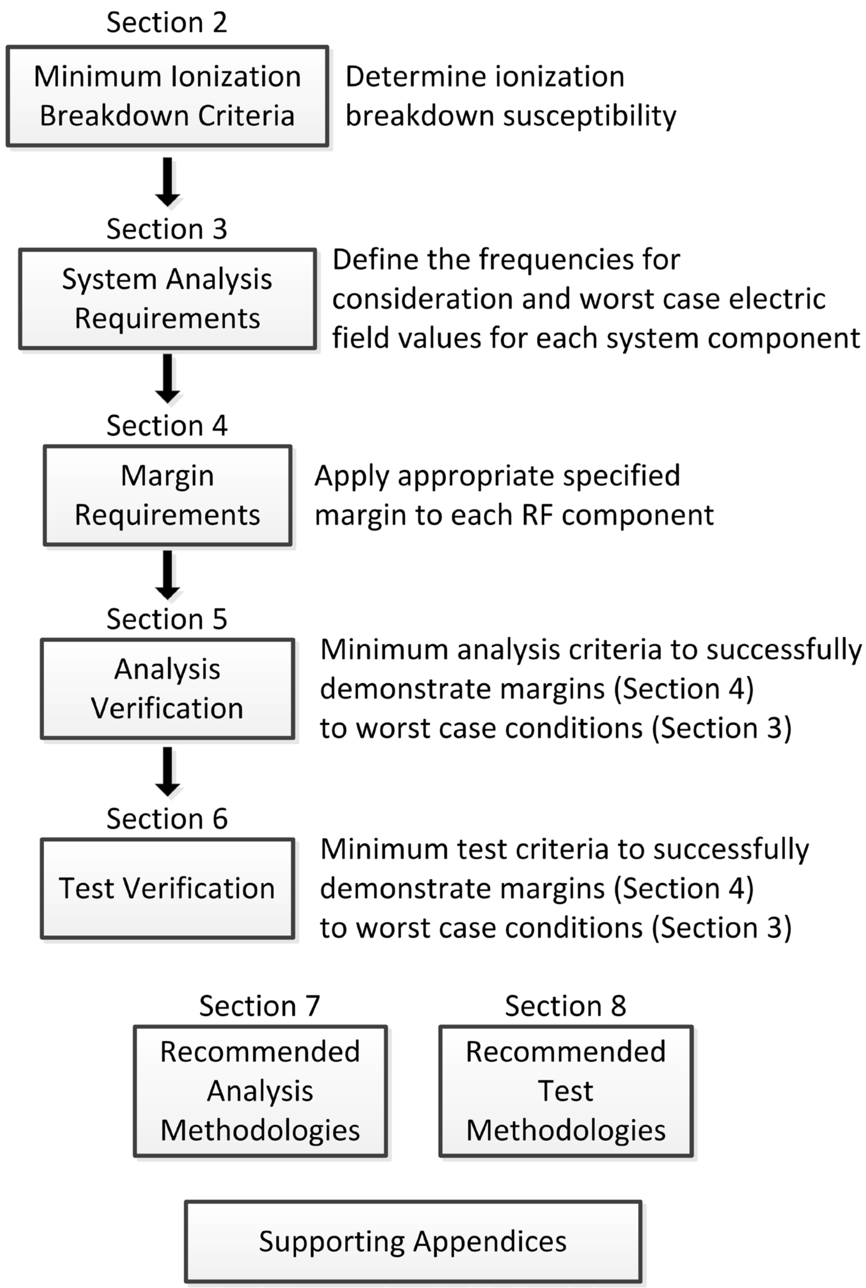


Figure 1.3. Applicability and document implementation for a typical RF system.

1.5 Ionization Breakdown Susceptible Systems, Components, and Missions

Ionization breakdown is a concern for any RF component with internal volumes where the presence of gas pressure greater than 1 x 10^{-4} Torr is possible. Such components may operate in this pressure region intentionally or they may be designed to operate in vacuum but are insufficiently vented such that increased pressure results from outgassing or other phenomena.

Examples of systems and components at highest risk for ionization breakdown include:

- Systems that operate during launch (atmospheric pressure to space vacuum), such as telemetry and control systems that operate continuously from ground to orbit. Even with sufficient venting, RF components in these systems operate over a range of internal pressures from ground to space.

- Systems where internal components are likely to operate at decreased internal pressures and subsequent lower breakdown thresholds. Examples include planetary landers, rovers, or very-high altitude systems.

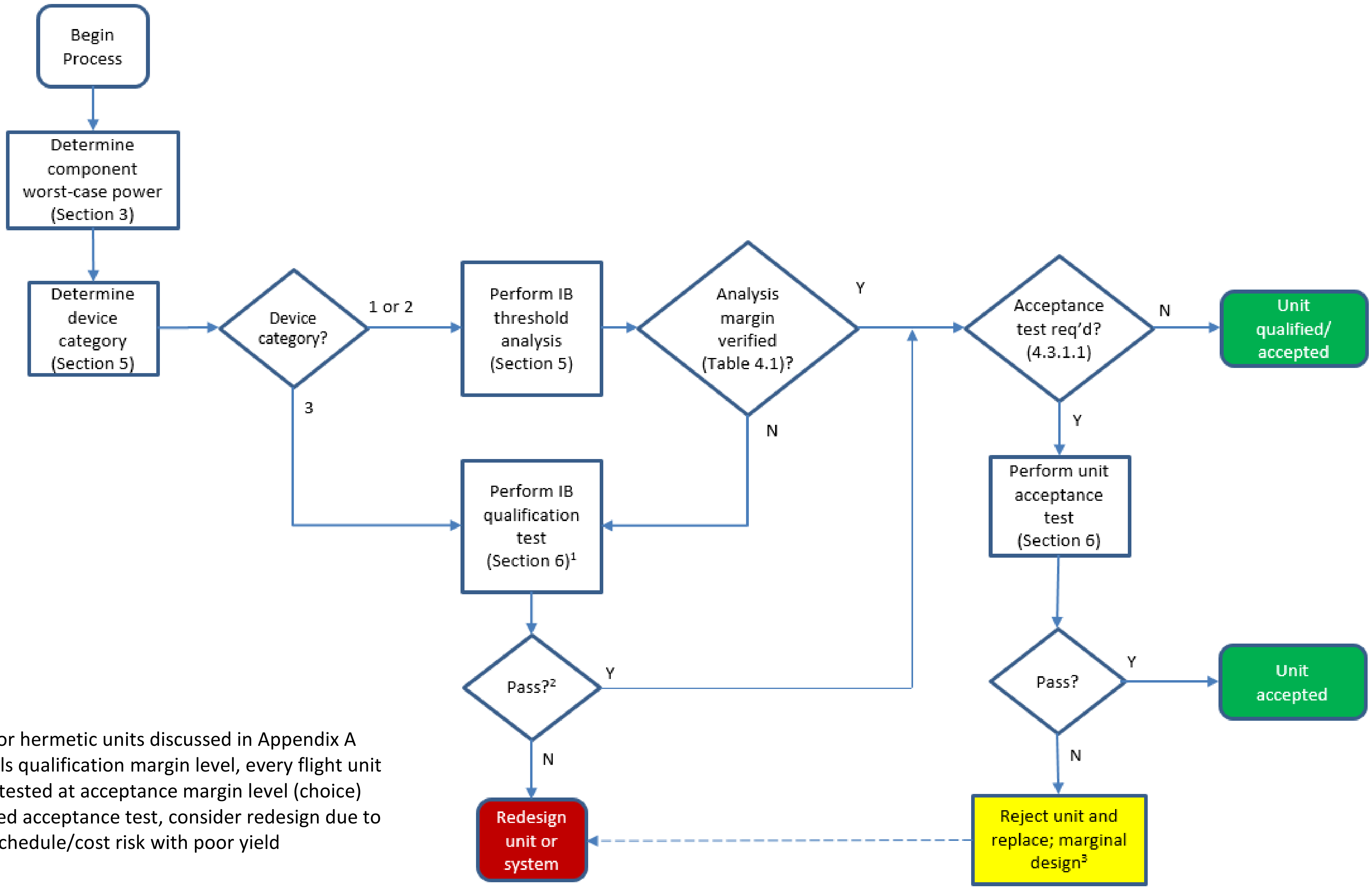
- Hermetically sealed components that could operate over a range of gas densities depending on gas leak rate and the lifetime of the mission/system.

- Unvented and poorly vented components with internal pressures greater than 1×10^{-4} Torr.

- Components with internal materials that may (continue to) outgas significantly when in operation, increasing pressure inside the unit.

1.6 Process Flow Chart for Ionization Breakdown Susceptible Unit Qualification/Acceptance and Verification

This document is intended to serve as a guide to allow an IB-susceptible device to be used on a spacecraft. The generalized process for device verification is provided in Figure 1.4. Section numbers relevant to each step are provided in the flow chart for reference.



1. Testing for hermetic units discussed in Appendix A
2. If unit fails qualification margin level, every flight unit can still be tested at acceptance margin level (choice)
3. With failed acceptance test, consider redesign due to increased schedule/cost risk with poor yield

Figure 1.4. Flow chart for verification process.

2. Minimum Ionization Breakdown Criteria

This section describes IB-susceptible geometries, pressures, and gases, and defines minimum ionization breakdown criteria.

2.1 Minimum Frequency

This document shall apply to all components within spacecraft RF systems that operate at frequencies above 100 MHz. This document does not address non-RF devices or direct current (DC) breakdown.

2.2 Applicable Gas Types

Different missions and environments may have different gas composition considerations. All gases should be considered as susceptible to ionization breakdown. Sources of gases other than the dominant gas in the environment may exist within a device. These include volatile contaminants from manufacturing or handling, adsorbed gases, and gases from the outgassing of materials elsewhere in the unit or spacecraft.

2.3 Voltages/Electric Fields

The threshold electric field for ionization breakdown in air is defined in Eq. (2.1). Below this electric field, ionization breakdown analysis or test is not required.

$$E_{threshold} = \frac{32 \cdot 2}{\sqrt{10}} \cdot f = 20 \cdot f \qquad [1]\ (2.1)$$

where $E_{threshold}$ = minimum peak electric field (V/cm) and f = frequency in GHz.

This expression includes 10 dB ionization breakdown power margin. Devices with electric fields higher than $E_{threshold}$ or devices operating with gases other than air or nitrogen shall be treated per this document's process. If the ionization rates of the operating gas environment are determined to be lower than that of air or nitrogen, $E_{threshold}$ may be applied.

If a component will operate in a vacuum, it shall be validated for multipactor breakdown. Refer to the companion document, Aerospace Report No. TOR-2014-02198, *Standard/Handbook for Radio Frequency Breakdown Prevention in Spacecraft Components*, for requirements.

2.4 Pressure Range

Ionization breakdown shall be considered in all components that can have gas pressure in excess of 10^{-4} Torr. For pressures above 10^{-4} Torr, multipactor breakdown still may apply (refer to TOR-2014-02198).

2.5 Venting

Venting requirements for devices that do not operate during launch shall allow sufficient gas flow conductance to maintain internal device pressures below 10^{-4} Torr before and during operation of each component. If such venting is provided, ionization breakdown requirements shall not apply unless pressure could rise above 10^{-4} Torr. Venting analysis shall include outgassing from all materials as a function of thermal history and shall include the effects of molecular gas flow conductance of all internal gas flow pathways.

3. System Analysis Requirements

This section provides the requirements for determining the bounding RF power to each component within the RF system. The worst-case peak power and average power applied to each component in the high power chain shall be computed for the applied waveform (single carrier, modulated, or multicarrier), component losses, VSWR, and fault conditions. These values can then be applied when deriving average and peak power test requirements and when computing the internal maximum electric fields in determining ionization breakdown margins.

Figure 3.1 provides an example generic high-power RF system block diagram. In this example, the worst-case amplifier output power is determined, and this power is decreased by component losses as it is passed downstream through the different components in the chain. Concurrently, downstream VSWR (assuming in-phase voltage addition) will lead to higher electric fields within the components. These system parameters are measureable and predictable in a bounding-case fashion, and they shall be included in determining the applicable power into each component in the system susceptible to RF breakdown.

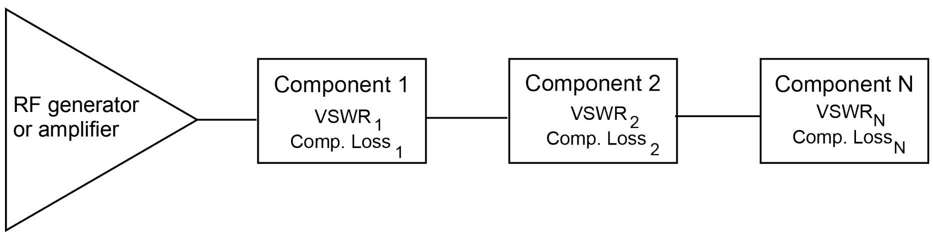


Figure 3.1. Example of a system for which component N must be evaluated for breakdown when exposed to an RF source that may be a single carrier, modulated, or multicarrier function.

The following requirements and process flow are provided in detail for the RF system analysis:

- Section 3.1: Frequency selection
- Section 3.2: Determine credible, yet recoverable failure modes that define which components, losses, and VSWR effects to include in the analysis
- Section 3.3: Determine worst-case output power from system amplifier(s)
- Section 3.4: Component losses based on losses of all upstream components
- Section 3.5: VSWR effects for each component from downstream reflections, assuming worst-case, in-phase voltage addition
- Section 3.6: Define effective power for each system component
- Section 3.7: Venting requirements
- Section 3.8: Other considerations

3.1 Frequency Selection

The frequency for verification (test and analysis) shall be the frequency or frequencies that produce the highest instantaneous electric fields in the component when it is operated. This includes flight-like operation, fault conditions, and test.

3.2 Definition of Failure Modes

Fault conditions shall be considered that could affect electric field strengths in the system components. These conditions may result from standing waves due to failed components, unintended redundancy

switch matrix configurations, overdrive scenarios, unlocked frequencies, unintended out-of-band power reflected back from downstream narrowband components, unintended thermal conditions, test system or procedural failures, or other conditions specific to the system being analyzed. The test power limits shall only consider single fault conditions, not the cumulative effect of multiple simultaneous faults. Fault conditions considered shall be credible and recoverable. Credible is defined as reasonable to consider that it may occur during the mission. If the failure is not recoverable, then consideration may not be necessary. For a non-survivable failure, the device shall avoid propagation to other units that are capable of supporting alternate or redundant pathways.

3.3 Worst-Case Amplifier Power

The maximum peak applied power calculation for several common amplifier configurations is described in this section. The maximum amplifier powers shall include temperature effects.

3.3.1 Single Amplifier (Single Carrier, Modulated, or Multicarrier)

The worst-case peak power output from a single amplifier shall be defined as the maximum saturated output power. It is not dependent on the number of carriers or modulation. The worst-case voltage shall be determined by peak power and local impedance of the device under consideration.

3.3.2 Non-Resonant Combining of Amplifiers (e.g., Multiport Amplifier)

Multiport amplifiers combine the power of individual amplifiers using non-resonant combiners (e.g., Butler matrices at the input and output). Any downstream component from the non-resonant-combining matrix shall be evaluated at a power level equal to $n \cdot P$, where n is the number of amplifiers and P is the saturated output power (see section 3.3.1) of each amplifier. Any upstream component from the non-resonant-combining matrix shall be evaluated per section 3.3.1.

Special consideration and analysis are necessary to determine the appropriate power levels for components and devices within the non-resonant-combining matrix. For example, internal components will generally have multiple ports with incident power that must be included in any engineering model (EM) or circuit simulation of the component. Also, the analysis must include fault conditions or alternate operating conditions that increase the power in non-primary paths (such as to an internal load).

3.3.3 Resonant Combining of Amplifiers (e.g., Output Multiplexers)

Resonant combining of amplifiers using output multiplexers, including diplexers and triplexers, can result in maximum peak powers equal to the voltage summation of the individual amplifier powers, represented as a peak power, n^2P, where n is the number of amplifiers combined and P is the saturated output power of each amplifier. The time duration for which these high peak powers may occur may be short depending on the number of carriers and the frequency spacing.

Components upstream from the combining circuit shall be evaluated per section 3.3.1. An effect of resonant combining, components at the common junction will have multiple carriers producing varied voltages relative to the incident power for those carriers. Care should be taken to analyze and include any voltage from adjacent carriers as well as the voltage in the primary carrier for all components at the common junction.

3.4 Component Loss

The worst-case input power to the component shall be determined by reducing the maximum peak power from the amplifier by the sum of the losses, L, for each upstream component (including resistive, combining, dielectric, etc.). The expression below for loss for a single two-port component assumes conjugate matching for maximum power transfer as a bounding case:

$$L(dB) = |S21(dB) - 10log_{10}\left(1 - 10^{\frac{S11(dB)}{10}}\right)| \tag{3.1}$$

S parameters shall be selected for minimum possible or expected loss.

3.5 VSWR/Reflected Power Enhancement

Mismatch at the output of the device will cause a voltage standing wave within the device resulting in higher voltages with in-phase voltage addition. Reflected power/VSWR contributions for each device shall be included in the worst-case system power analysis. The largest downstream VSWR component specification shall be used to scale the effective device power to account for higher gap voltages.

The power enhancement due to in-phase voltage addition, E_{VSWR}, is given below in dB:

$$E_{VSWR}(dB) = 20 \cdot log_{10}\left(\frac{2{\cdot}\mathrm{VSWR}}{\mathrm{VSWR}+1}\right) = 20 \cdot log_{10}\left(1 + 10^{\frac{-\mathrm{RL}}{20}}\right) \tag{3.2}$$

Note that *RL* is return loss in positive dB. As in section 3.4, downstream power reflections will also be reduced by losses. Assuming lossless components for reflected power enhancements shall be considered a bounding case.

3.6 Effective Component Power for Analysis and Test

The worst-case power requirement for each component shall be calculated via the following equation:

$$P_{WC}(dB) = P_{amp}(dB) - L(dB) + E_{VSWR}(dB) \tag{3.3}$$

where P_{wc} is the worst-case component power, P_{amp} is the bounding amplifier(s) power given in section 3.3, L is the aggregate loss of all the components calculated in section 3.4, and E_{VSWR} is the reflected power enhancement given in section 3.5.

3.7 Venting Requirements

This document provides guidelines to ensure that a device is capable of handling its intended power from atmospheric pressure through critical pressure, where breakdown threshold is the lowest. As the pressure transitions to vacuum, the companion multipactor document, TOR-2014-02198, applies.

That said, intentional vent paths are required in any non-hermetic RF device operating in a vacuum environment. Vent holes shall be placed in a device for venting to the high vacuum region (less than 10^{-4} Torr). The venting time constant is defined by the ratio of the device or cavity volume divided by the total gas flow conductance for all venting from this region. However, once all the gas in the volume has vented, the internal pressure is controlled by the amount of outgassing and the total gas flow conductance to the vacuum chamber or to space. In order to accommodate outgassing that could occur during operational thermal loading, sufficient venting shall be incorporated to reduce any associated pressure increases.

3.8 Other Considerations

3.8.1 Test VSWR Environment

The component may be exposed during factory testing to load environments that are different than the operational environment and these must be taken into account when specifying the test power. Examples include poor matching conditions due to vacuum chamber feedthrough connections or test equipment conditions such as test cabling and imperfect loads. Conversely, test environments may present more ideal load conditions than those expected for the operational system. This too must be taken into account when specifying test power levels. Components tested in conjunction with antennas need special consideration of the radiating environments during test. Imperfect absorber mismatch and consideration of multiple reflections in a thermal vacuum environment should be assumed when determining the reflected power from downstream components.

3.8.2 Gas Compositions for Test

Test methods for ionization breakdown may require multiple venting cycles in the test vacuum chamber. Both dry air and nitrogen are acceptable gases to use for chamber testing if the operating environment is either air or nitrogen. Systems that operate in other gas environments shall take the operating environment into account. This can be done by testing using the operational gas composition that produces the lowest breakdown threshold, or by demonstrating that the operational gas composition produces higher breakdown thresholds than dry nitrogen.

4. Ionization Breakdown Margin Requirements

4.1 Margin Requirements

Table 4.1 provides minimum power margin requirements for analysis and test of ionization breakdown.

- These margins shall only be appropriate when verified using the methods and requirements given in section 5, Analysis Verification Requirements, and section 6, Test Verification Requirements.
- These margins shall be based on input power defined using the methods and requirements given in section 3.
- Analysis categories are defined in section 5.

Table 4.1. Margin Requirements for Analysis and Test

Test (dB)		Analysis (dB)
Acceptance	Qualification	Qualification
3	6	10*
*Analysis category 3 cannot be qualified by analysis		

4.2 Factors Influencing Margin Requirements

Section 3 quantifies the system-level worst-case conditions while removing uncertainties in the power level determination. Due to additional uncertainties about the characteristics of a device, margin is required. The first 3 dB in acceptance testing is for handling, processing, and end of life effects that cannot be predicted. The next 3 dB for qualification testing (bringing the sum to 6 dB) is for unit-to-unit variability factors as only one unit is being tested. The final 4 dB for qualification by analysis (bringing the sum to 10 dB) is for uncertainties in the modeling capability that are not present in testing.

4.3 Margin Verification Methods

Margins specified in Table 4.1 shall be verified by component qualification and, when applicable, acceptance test. Qualification shall be required for all components. Definitions and requirements for qualification and acceptance are provided below. Minimum margin verification requirements for qualification/acceptance via analysis or test are provided in sections 5 and 6, respectively.

4.3.1 Component Qualification

Component qualification is intended to demonstrate that the component design and manufacturing processes provide adequate margin for ionization breakdown. Qualification also ensures the acceptance program will produce hardware that will meet the component requirements with margin. Qualification testing validates the acceptance verification process including validation of test techniques, equipment, and procedures.

Component qualification shall be required for all device types. Qualification by analysis can be considered for device category 1 and 2 only. Any component operating at a new frequency with respect to prior qualification conditions shall require additional qualification at these new conditions. Operation at

higher power levels shall require additional qualification if there is insufficient margin per Table 4.1 at the increased level with respect to prior qualification power levels.

For new component development, risk-reduction testing on an engineering model/prototype is recommended prior to proceeding into production of qualification units. Upper-limit capability testing, in which the component power is increased until breakdown is observed, is also recommended for new designs.

4.3.1.1 Lot Acceptance by Qualification

The following criteria shall be met for a qualification analysis/test to verify acceptable margins for all flight units within a manufacturing lot. For this case, unit-level acceptance testing (section 4.3.3) is not required. All of the following criteria must be met:

- Worst-case component electric field values shall be computed per section 3
- Qualification by test: Qualification unit shall be built with same parts, materials, assembly processes as flight unit.
- Qualification by analysis: Model shall be representative of worst-case geometry and local fields expected within all flight components

4.3.1.2 Qualification by Similarity

Qualification by similarity shall be allowable for consideration if all geometries affecting ionization breakdown performance and the frequency of interest are determined to be identical to prior qualification. Description of any device changes and similarity to prior qualification shall be provided to the customer. The customer shall provide approval on qualification by similarity applicability to each component under consideration.

4.3.2 Component Proto-Qualification Testing

Proto-qualification test conditions shall demonstrate the required breakdown margin without thermally overstressing the component and invalidating its acceptable use for flight.

The proto-qualification peak power for ionization breakdown shall be the same as the qualification peak power. Average power in proto-qualification testing shall not exceed maximum operating average power. Test temperatures shall be within the proto-qualification temperature requirements.

4.3.3 Flight Component Acceptance Testing

If a device is not successfully qualified by analysis or qualification test, acceptance testing of each unit is required. Additionally, all category 3 components shall undergo acceptance testing of each flight unit to verify workmanship and manufacturing/unit-to-unit variations. Component acceptance testing is conducted to demonstrate ionization breakdown-free operation with margin for each deliverable unit. Testing shall demonstrate that workmanship and manufacturing is sufficient to prevent breakdown under worst-case flight conditions plus margin. Acceptance testing should encompass worst-case conditions and applications, and test conditions are designed to allow repeated testing of the component with no degradation.

Any component not satisfying conditions in section 4.3.1.1 shall satisfy margin requirements via acceptance test per Table 4.1.

The following criteria shall be met for valid component acceptance:

- Shall be performed on each flight unit
- Worst-case component power shall be computed per section 3
- Margin per Table 4.1 test margin shall be demonstrated to section 3 worst-case power
- All minimum test verification requirements (section 6) shall be met

4.4 Risk Management Process

This document is designed to minimize ionization breakdown risk, and thus stipulates a suitable approach to analyzing and testing hardware. Any departure from margin requirements (Table 4.1) or deviations from the outlined process (Figure 1.4) shall require specific and documented disposition and technical rationale for the acceptance of higher risk associated with lower margin requirements. Customer and supplier shall agree on additional risk imposed by a departure from specified requirements.

5. Analysis Verification Requirements

There are two steps to verification by analysis when considering ionization breakdown. The first is to determine the local electric field. The second is to assess the threshold for ionization breakdown. Analysis as discussed in this section shall be done to critical pressure for dry air. Analysis methodologies are determined by analysis category, which will be described in detail in section 5.3. A general description of analysis approach by category is provided in Table 5.1. Table 5.2 provides a list of the minimum criteria for analysis verification.

Table 5.1. Analysis Methods by Category

	Category 1	Category 2	Category 3
Determination of Local Electric Field	Analytical	Numerical	N/A
Assessment of Breakdown Electric Field	Equation (5.1) or Equation (5.2)	Equation (5.1) or Numerical	N/A

Table 5.2. General List of Analysis Verification Requirements

Section	Analysis Requirements	Description/Summary
5.1	System parameters	Each component, each gap
5.2	Breakdown theoretical curves	Determine appropriate curve
5.3	Electric field analysis	Process for each category
5.4	Analytical margin determination	Determination of margin by comparison to known/modeled threshold
5.5	Analysis process	Overall flow chart

5.1 Implementing System Parameters into Analysis

For each component and susceptible gap, the worst-case analysis power shall be derived via methods provided in section 3 for baseline internal electric field determination. Electric field maps at each frequency of interest shall be scaled to input power levels given in section 3.

An analysis shall be performed for each frequency specified by section 3.1. Additional analyses may be necessary for cases with other frequencies of concern and/or consideration.

5.2 Breakdown Theoretical Curves

Ionization breakdown occurs when conditions exist within a volume for which the rate of growth in an electron population exceeds the rate of loss. Electron population grows due to ionization of the gas in the volume. Loss rates are driven by contributions from attachment and diffusion. Appendix B contains a full discussion of the theory of ionization breakdown.

5.2.1 Rule-of-Thumb Breakdown Curve

A rule-of-thumb ionization breakdown curve for air relating the breakdown peak electric field to the frequency and pressure is provided by Woo and DeGroot: [1]

$$\frac{E}{f} = 32 \cdot \sqrt{2} \cdot \sqrt{(p/f)^2 + 2} \tag{5.1}$$

where peak electric field, frequency, and pressure are given in V/cm, GHz, and Torr. As pressure goes to zero, Eq. (5.1) will approach the minimum breakdown threshold discussed in section 2.3. Note that the 20·f minimum criteria also includes 10 dB of margin. This curve is plotted in Figure 5.1.

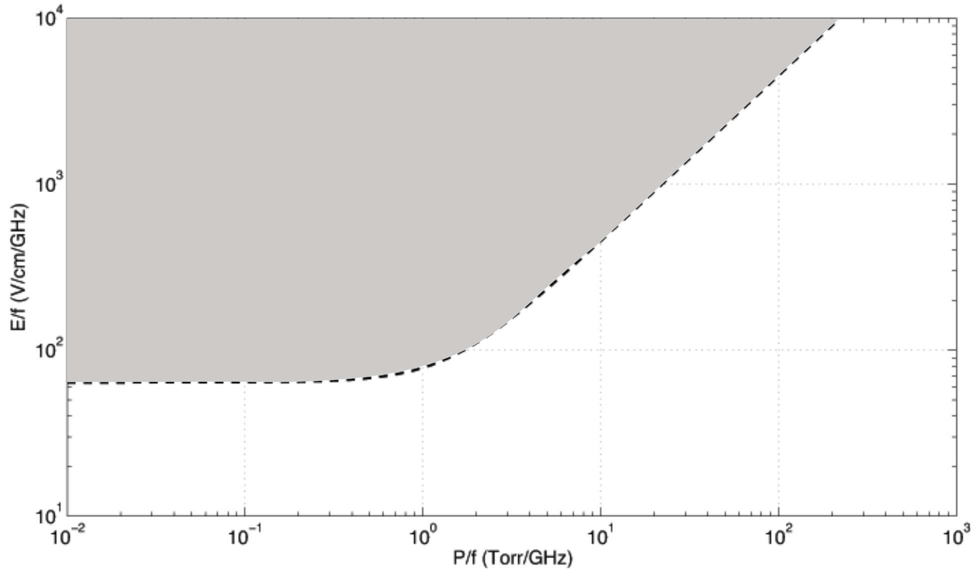


Figure 5.1. Region of ionization breakdown susceptibility defined by rule-of-thumb curve [Eq. (5.1)].

5.2.2 Semi-Empirical Breakdown Curve

If the worst-case electric field exceeds the breakdown field given by Eq. (5.1), and the device is a category 1 or 2, the semi-empirical breakdown curve shall be used. This curve requires knowledge of a clearly defined diffusion length L_D, which depends on the physical dimensions of the device and applies to simple, canonical geometries. Diffusion length is the characteristic length over which an electron must travel to escape the breakdown region. The semi-empirical curve is defined by Eq. (5.2):

$$E = 5.3 \cdot p \left[1 + \left(\frac{2\pi f}{p \cdot 5.3}\right)^2\right]^{0.5} \left(L_D^{-2} \left(\frac{1140}{p}\right)^2 + 6.4 \cdot 10^4\right)^{1/5.34} \quad [2]\ (5.2)$$

Where E is peak electric field in V/cm, p is pressure in Torr, diffusion length terms are in cm, and f is frequency in GHz.

The diffusion length, L_D, is given for some basic geometries in Table 5.3. [3] For use in Eq. (5.2), the expressions are given in terms of L_D^{-2}. The length, L, and radius, R, in the formulae are physical dimensions in the device. Each susceptible region shall be examined.

Table 5.3. Diffusion Lengths for Common Geometries (Adapted from Reference [3])

Structure	L_D^{-2}
Parallel plate geometry **Length L**	$\left(\pi/L\right)^2$
Cylindrical Resonator (TM_{010} mode) **Radius R, length L**	$\left(2.405/R\right)^2 + \left(\pi/L\right)^2$
Circular waveguide (TE_{11} mode) **Radius R**	$\left(2.405/R\right)^2$
Rectangular waveguide (TE_{10} mode) **Dimensions a x b**	$\left(\pi/a\right)^2 + \left(\pi/b\right)^2$
Coaxial line (TEM mode) **Inner radius a, outer radius R**	$R \to a$: $\pi^2/(R-a)^2$ $R/a \to \infty$: $\left(2.405/R\right)^2$

5.2.3 Applicable Gases

Analysis shall be done for dry air unless the device will be exposed to another gas with known reaction rates. Eqs (5.1) and (5.2) are specific to air. Devices which operate in environments other than air shall be subject to test.

5.2.4 Temperature Considerations

Dimensional changes from the device's operating temperatures shall be analyzed for worst-case conditions.

The minimum breakdown threshold does not depend on gas temperature when it is below 2000 K. Therefore, devices with gas temperatures below 2000 K, operating from atmospheric pressure to a vacuum environment, do not require temperature adjustments to the minimum breakdown analysis. [2]

For devices operating at pressures that stay above the critical pressure, temperature shall be considered. At a fixed pressure above critical pressure, the breakdown threshold will change as temperature changes (see section 7.4).

5.2.5 Material Selection

Ionization breakdown analysis can be performed independent of the material properties, other than the properties required for proper electric field analysis.

5.3 Local Electric Field Analysis

For each component and susceptible geometry, electric fields in the suspected ionization breakdown region shall be determined. Minimum requirements for determining these fields are categorized by device category, which are tailored by different analytical methods as described below.

All susceptible components defined from section 2 shall fall into one of three categories that are differentiated by the minimum analysis criteria required to verify devices of that category. Table 5.4 shows device categories that determine what level of analysis is sufficient to qualify the component.

An important factor in category definition is the ability to determine diffusion length. Diffusion length is a characteristic length used to describe diffusion losses in assessment of ionization breakdown. Diffusion length is not a physical dimension of the device; see Table 5.3 for definition.

Table 5.4. Device Categories

Category	Definition	Device Features or Examples	Analytical RF Breakdown Level Determination (Section 5)
1	Simple geometries. Bounding diffusion length can be determined	Resonator cavity, transmission lines	Require analytical curve (section 5)
2	Diffusion length cannot be directly determined	Impedance transitions, filters, multiplexers, isolators	Require appropriate numerical multidimensional plasma breakdown simulator
3	Uncontrolled geometries or workmanship variability	Potted device, tuning screws in critical areas	N/A

The special case of hermetic devices is addressed separately in Appendix A. A higher level of category analysis may be applied to a device of a lower category at the discretion of the analyst.

5.3.1 Category Definitions

5.3.1.1 Category 1 Component

In category 1, the device consists only of simple (canonical) geometries (e.g., coaxial, waveguide, and parallel plate transmission lines). The effective diffusion length is well characterized or assumed to be zero. Computations or estimates of maximum local electric fields are used in the rule-of-thumb or semi-empirical expression to determine the breakdown threshold (see section 5.2).

5.3.1.2 Category 2 Component

Category 2 devices may contain composite geometries, defined as a collection of simple geometries, or complex internal geometries where effective diffusion length cannot be easily determined. In such cases, the effective diffusion length may be much shorter than internal component dimensions with homogeneous electric fields. For these devices, a bounding diffusion length cannot be determined and thus may be verified either via the rule-of-thumb equation [Eq. (5.1)] or numerical breakdown analysis.

A category 1 device that is not determined to have sufficient margin may be analyzed as a category 2 device for verification purposes.

5.3.1.3 Category 3 Component

Any component that does not fit the description of a category 1 or 2 device shall be considered category 3. This category includes components with undefined or uncontrollable gaps that include unknown unit-to-unit variation, workmanship, and geometric tuning elements. In these cases, the diffusion length cannot be clearly determined for all units or geometric variation can occur during the component life, including ground-test and on-orbit operation.

Some components with uncontrollable, but knowable, gaps (e.g., measurement of screw depth post-tuning) may be considered category 2 if the analysis is performed for the worst-case condition and this condition is confirmed by direct measurement during acceptance testing. Measurement and recordkeeping

of an uncontrollable gap may be waived if such a gap is not the limiting or critical geometrical element, such as a tuning screw in a low field location.

5.3.2 Analysis Requirements by Category

5.3.2.1 Category 1

Category 1 components shall have analytically-determined electric field in the breakdown susceptible region. Category 1 components shall have a single computed electric field for the breakdown-susceptible region. Furthermore, category 1 devices shall have an analytically-determined breakdown electric field as determined by geometrical constraints.

In cases with dielectric layers of different dielectric constants (or stacked dielectrics), the electric field shall be calculated in the vacuum gap region including impedance changes due to the presence of the dielectric layers. The field values in the vacuum gap shall be considered for ionization breakdown. Application of category 2 methods shall be required if analytical solutions are not possible for the breakdown region.

For devices where ionization breakdown is nominally prevented by a partial or full dielectric fill, potential gaps in the filled volume shall be considered. Gaps may be realized through differential thermal expansion, machining tolerances, or workmanship limitations. The largest possible gap shall be considered.

5.3.2.2 Category 2

Category 2 components shall require three dimensional (3-D) electric field solvers or tools to determine all internal fields for the component. This 3-D full electric field solution shall be incorporated into a suitable plasma simulation tool to determine breakdown thresholds. The breakdown power threshold shall be determined by either Eq. (5.1), which does not require knowledge of the geometry of the breakdown region, or a plasma simulation tool, applied to all potentially susceptible geometries within the device. For devices that utilize DC electric or magnetic fields for device operation, multipactor suppression, or possess DC fields that can significantly affect electron trajectories, these fields must be included in the numerical simulation. If such a tool is not available, then the device shall be tested.

5.3.2.3 Category 3

Category 3 components shall be qualified by test. Qualification and acceptance test screening is required for these components to ensure proper operation over life. Devices that operate with gases that are not nitrogen or air shall be treated as category 3.

5.4 Analytical Margin Determination

Each minimum electric field computed in section 5.5 shall be compared to the baseline threshold electric field given by Eq. (5.1) or (5.2). Ionization breakdown margin shall be computed by the equation below:

$$Margin\ (in\ dB) = 20log_{10}\frac{E_{threshold}}{E_{local}} \tag{5.3}$$

where $E_{threshold}$ is the electric field from section 5.2 at the determined pressure and frequency, and E_{local} is the computed electric field from section 5.5.

5.5 Analysis Process

The following describes the general process for multipactor margin verification by analysis.

1. Identify necessary method to determine local electric field in the susceptible region.

    a. Category 1: Analytically determine peak electric field in susceptible region.

    b. Category 2: Numerically determine peak electric fields in the multidimensional susceptible region.

2. Category 1: Scale each determined electric field to the worst-case power by the following equation, where $P_{worstcase}$ is calculated in section 3, and $P_{analysis}$ is the input power used in the analysis:

$$E_{scaled} = E_{analysis}\sqrt{\frac{P_{worstcase}}{P_{analysis}}} \tag{5.4}$$

    a. Compare the scaled electric field(s) to known threshold(s) given in Eq. (5.1). Determine margin by the equation in section 5.4.

        i. If the margins in Table 4.1 are satisfied, then margin verification is complete.

        ii. If margins in Table 4.1 are not met, and diffusion length in the breakdown susceptible region is known, compare the scaled electric field(s) to known threshold(s) given in Eq. (5.2). Determine margin by the equation in section 5.4.

        iii. If margins in Table 4.1 are still not met, then determine if evaluation at a higher category is possible/needed (i.e., analyze category 1 component as category 2). If so, repeat process starting with step number 1.

3. Category 2: Input the 3-D electric field model into a plasma simulation tool. Determine the threshold breakdown power and compare to $P_{worstcase}$ derived in section 3.

    a. If margins in Table 4.1 are satisfied, then margin verification is complete.

4. Category 3 components as well as any component not meeting the analysis verification requirements shall undergo redesign or verification by test.

For cases in which category 1 device analysis is insufficient, the device may be analyzed at a higher category level (e.g., apply numerical analysis to category 1 device for improved analysis fidelity).

The flow diagram in Figure 5.2 summarizes the baseline analysis process above.

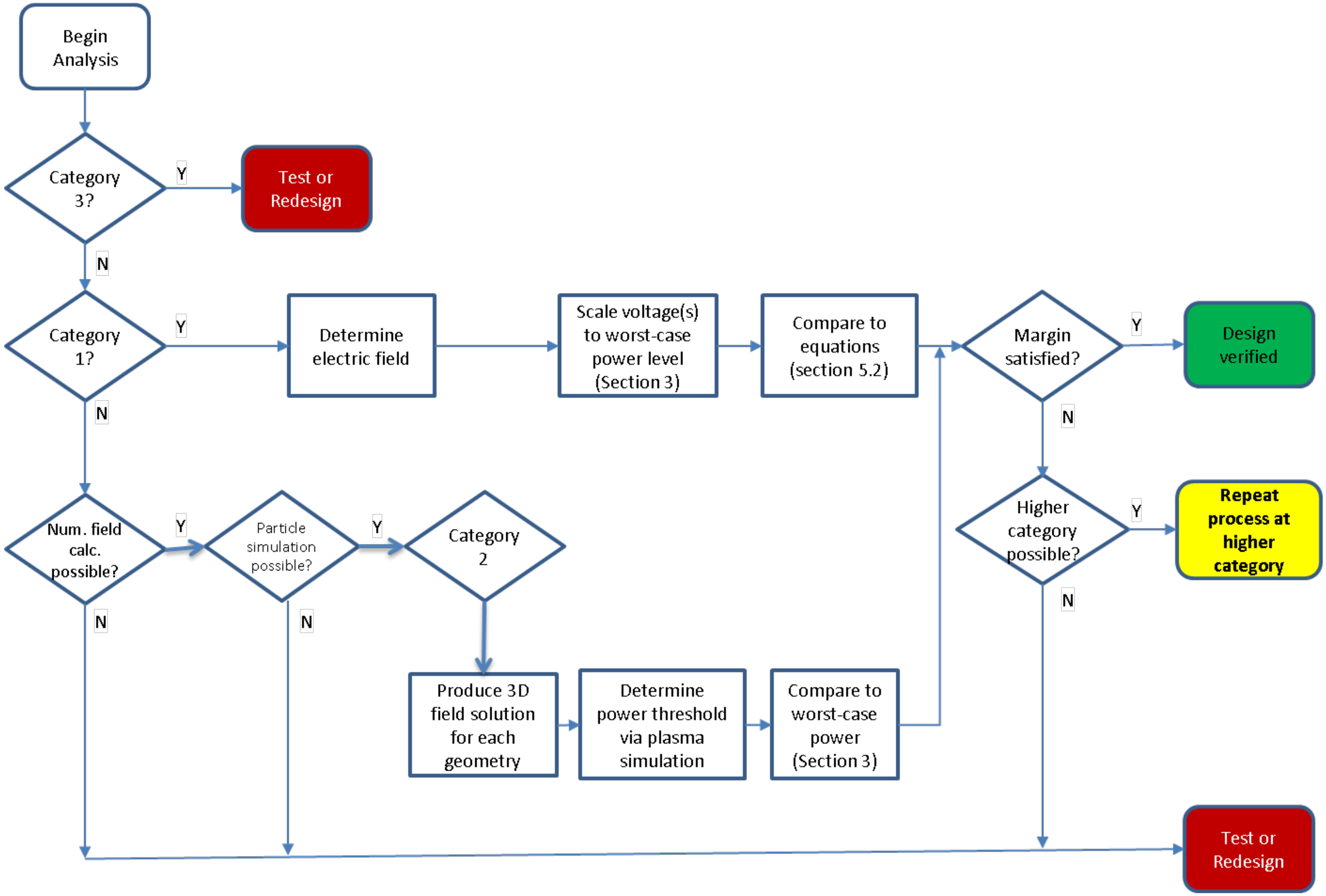


Figure 5.2. Baseline analysis process.

6. Test Verification Requirements

This section outlines the basic minimum criteria for requirement verification via ionization breakdown test. The requirements are summarized in Table 6.1. Wherever possible, any test parameters should be treated as "test like you fly," meaning that flight-like conditions should be replicated in the test.

Table 6.1. Summary of Minimum Test Requirements for Margin Verification

Section	Test Requirements	Description/Summary
6.1	Documentation	Detailed test procedure
6.2	Breakdown detection methods	At least 2 methods, at least one global
6.3	Test setup verification	RF breakdown-free test setup Demonstration of breakdown detection
6.4	Duty cycle	Based on simultaneous application of average and peak power with margin
6.5	Pulse length	10 microsecond minimum, must be detectable
6.6	Electron seeding	Required for pulse lengths less than 1 ms
6.7	Pressure	Choose a pressure profile to bound worst-case environment
6.8	Thermal	Operational temperature(s)
6.9	Data acquisition	Continuous monitoring at sampling rates sufficient to detect breakdown in one pulse
6.10	Pass/fail criteria	No indication of breakdown on any detection method is a passing result

6.1 Documentation

A detailed test procedure shall be provided for each flight device that meets the criteria of this section. The customer shall approve the test procedure prior to test start.

6.2 Breakdown Detection Methods and Monitors

6.2.1 Breakdown Detection Methods

Ionization breakdown events shall be detected by means of global and/or local diagnostics. Global diagnostics are defined as detection of breakdown occurring without knowing the specific location of the breakdown. Local diagnostics are defined as detection at the specific location of the breakdown. Diagnostic sensitivity is defined in section 8.5.

The detection methods that are required for ionization breakdown testing shall include at least two independent detection methods. At least one global detection method shall be used.

6.2.2 Test Monitors

Additional device monitors that are required for ionization breakdown testing shall include:

- Incident power monitor (peak and average)
- Reflected power monitor (peak and average)
- Output power monitor (peak and average, if available)

- Temperature of unit
- Chamber pressure

Peak power may be used as a detection method only if high-speed detection (such as with a diode detector) is used.

6.3 Test Setup Verification

Prior to flight article testing for RF breakdown margin verification, the test setup shall be verified. This includes the ability to operate free of ionization breakdown, the ability to detect breakdown, and the ability to provide the test pressure profile.

6.3.1 Breakdown-Free Verification

With no device under test (DUT) present, RF energy shall be applied to the test setup at the test frequency and at least the maximum test power to demonstrate breakdown-free operation within the test components, system, and test diagnostics. During this verification, the setup shall be exposed to the test pressure profile. There shall be no evidence of breakdown.

6.3.2 Known Breakdown Device

A device with a known breakdown threshold shall be tested in the identical test configuration as the DUT. The verification test shall be performed at the same frequency as the device under test. Evidence of successful breakdown detection shall be demonstrated with all detection methods, simultaneously. The known breakdown may be a multipactor breakdown or an ionization breakdown. Evidence of successful breakdown detection shall be demonstrated before and after flight unit testing.

6.4 Duty Cycle

To verify a device by test, the maximum average power (section 3) need not exceed the operational average power. For continuous wave (CW) components, testing the component with margin may cause the average power to overstress the device thermally. In such cases, a duty cycle shall be employed to match worst-case average power with peak power with the specified margin. No additional average power margin requirement is provided in this document.

6.5 Pulse Length

The pulse width shall be greater than 10 microseconds. The detectability of the chosen pulse width shall be confirmed in the known breakdown device test from section 6.3.

For test configurations in which electron seeding levels are lower than on-orbit (e.g., all laboratory radioactive sources), test-like-you-fly exceptions for longer pulse lengths are recommended to decrease threshold dependence on electron seeding and provide more time response for common diagnostics.

6.6 Electron Seeding

Electron seeding is defined as the introduction of free electrons to the susceptible regions within the DUT. Electron seeding is required when the pulse width is less than 1 millisecond or for duty cycles less than 5%.

The electron seeding source shall provide local electrons to breakdown risk area. Consideration for the seed strength shall include radioactive isotope selection, DUT housing material, wall thickness, as well as physical access to internal geometries.

6.7 Pressure

6.7.1 Gas

Test shall be performed with the gas to which the unit will be exposed in operation. If that gas is air, dry nitrogen shall be allowed as a substitute.

6.7.2 Pressure Range

Testing shall occur at all pressures above 10^{-4} Torr at which the unit will operate. Pressure can transition upwards or downwards.

6.7.3 Pressure Profile

The rate at which the pressure changes in test shall be no faster than the pressure transition rate of the unit during operation. Power shall be applied continuously throughout the pressure profile. Intermediate discrete pressures with soak times can be used to ensure rate is slower than operational pressure transition rates.

6.7.4 Vacuum Soak

After the pressure profile is complete, the chamber pressure shall be held for a period long enough to ensure device internal pressure has equilibrated to chamber pressure. Duration may be adjusted depending on device and system venting characteristics. If the pressure started at the high pressure, this final pressure must be below 10^{-4} Torr. If the pressure started at the low pressure, this final pressure must be at the final high pressure.

6.7.5 Repressurization

If more than one pressure cycle is applied, the chamber shall be vented with gas in between cycles and allowed to soak to ensure all areas are fully pressurized before the next pressure cycle.

6.7.6 Venting

The test article and test equipment shall have venting features such that the internal pressure of any the devices quickly reaches a pressure which is approximately the same as the chamber pressure. If the test article does not have defined vent features by design, venting features may need to be added in order to test.

6.8 Thermal

Testing shall be performed at the temperature(s) of the device when it is in operation at pressures greater than 10^{-4} Torr.

6.9 Data Acquisition

All items listed in section 6.2 shall be continuously monitored and recorded throughout test for post-test review. Data acquisition rates for detection methods shall be fast enough to capture transient events

occurring within a single pulse. Other parameters, such as temperature and pressure, shall be monitored at a reasonable rate with respect to the speed of changes during test. Further recommendations are given in section 8.9.

6.10 Pass/Fail Criteria

Pass/fail criteria are specific to the attributes of the device under test and chosen detection methods and shall be stipulated as appropriate for each detection method.

RF breakdown shall be indicated by simultaneous detection on a minimum of two diagnostics or a single local diagnostic. Simultaneous increase for any duration over a pre-determined threshold shall be considered positive indication of RF breakdown. Threshold levels shall be specified within the test documentation (section 6.1). Detection on a single global diagnostic shall be investigated and disposition determined in each case.

In order to successfully verify margins by test, the full-recorded data history (section 6.9) shall be provided to verify component performance with no simultaneous detection of breakdown at any point. Additionally, evidence of successful detection on the known breakdown device shall be provided.

Short bursts of ionization breakdown that are not sustained and/or difficult to repeat shall be fully considered and evaluated by the pass/fail criteria. If determined to be a positive indication of breakdown and test failure, no subsequent testing on the failed DUT shall be considered to exonerate the original failure.

7. Analysis Methodology

This section describes methods and consideration for performing ionization breakdown analysis for an RF device or assembly. The following topics are addressed:

- Steps for determining ionization breakdown threshold at the device level
- Guidance and considerations for applying analysis techniques
- Analysis methods for risk assessment

The foundation of any breakdown analysis is knowledge of the electromagnetic field distribution within the device. An analytical or numerical model capable of providing accurate field quantities and distributions is the baseline requirement of all analysis methods. In support of a field solution, the basic inputs of frequency, RF geometry, and RF material parameters are required for any ionization breakdown analysis. Minimum requirements for these inputs are described in section 5.

7.1 Category 1

7.1.1 Steps for Determining Expected Breakdown Power

In cases where worst-case power is not known, or when the analysis goal is the predicted breakdown power level for a device, a different process is used. The expected breakdown power level is calculated in absence of all system factors that contribute to a worst-case power analysis in section 3 (e.g., VSWR). Recommended steps for this process are outlined below:

1. Calculate the peak electric field within the device.

    a. Category 1—analytical field solution for a single gap

    b. Category 2—numerical field solution for complex gaps

2. Use the ionization breakdown threshold curves from section 5.2 to determine the predicted breakdown electric field at each pressure and frequency under analysis.

3. Compute the power breakdown threshold by scaling the analysis to expected breakdown electric field.

$$P_{BD} = P_{analysis} \cdot \left(\frac{E_{BD}}{E_{analysis}}\right)^2 \tag{7.1}$$

7.1.2 Limitations and Considerations

The accuracy of category 1 methods relies on the applicability of the theoretical electric field breakdown curves provided in section 5.2.

The rule-of-thumb equation [Eq. (5.1)] does not consider gas diffusion or temperature and is conservative compared to the semi-empirical curve [Eq. (5.2)]. Equation (5.2) makes assumptions about plasma diffusion, gas composition, and gas temperature. Furthermore, this curve is applicable only if diffusion length is well-known, which requires a specific geometry described in Table 5.2. For situations that diverge from these assumptions, the accuracy of this analysis method decreases.

If the method used to solve for field strength does not have the resolution or capability of accurately predicting the field strength in the gap, use the relative dielectric constant of the material, ε_r, times the field strength in the dielectric material as a worst-case condition. ε_r is the ratio of the material dielectric constant to the free space dielectric constant, ε_0. If the bounding values for the worst-case condition do not yield sufficient margin, test is required.

7.2 Plasma Simulation tool considerations

Similar to the multitude of electromagnetic field solution methods, there are multiple plasma physics simulation tools that may be applied for ionization breakdown analysis. At a minimum, the algorithm must accurately simulate plasma attachment and diffusion rates, as well as incorporate the multidimensional electromagnetic fields solution.

Furthermore, if there are static electric or magnetic fields in the system, these must be accurately treated in both the electromagnetic field solution and plasma simulation tool, or the device must be tested.

7.2.1 Recommended Steps for Analysis

1. Generate a representative 3D RF device model to anchor numerical EM field solution. At a minimum, the model must be capable of demonstrating accurate RF electrical performance (S-parameters) matching RF designed specifications or measurements

2. Invoke a plasma simulation tool using the RF device model to determine P_{BD}

3. Determine power margin. Calculate device margin using worst-case power obtained from section 3.2

7.3 Analysis for Risk Assessment

In cases where verification by analysis is not permitted or possible, a simplified analysis for risk assessment is recommended to provide some basic confidence in the device design. This simplified analysis is not adequate for device qualification by analysis. Examples of risk assessment analysis include applying a lower category analysis method to higher level device or by applying a hybrid RF circuit model approach.

7.4 Temperature Considerations

For devices operating at pressures that stay above critical pressure, the gas temperature affects the breakdown field. As gas temperature changes, gas density also changes, affecting the breakdown field as seen in Figure 7.1. For gas temperatures below 2000 K, the value of the minimum breakdown field does not change. [2]

For gas temperatures above 2000 K, the minimum breakdown field decreases as temperature rises (see Figure 7.2). This document does not consider gas temperatures above 2000 K.

Equation (7.2) can be used for analysis of devices operating at dry air temperatures below 2000 K. It is the same as Eq. (5.2), but modified to include temperature.

$$E = 5.3 \cdot p^* \sqrt{1 + \left(\frac{2\pi f}{\nu_c}\right)^2} \cdot \left(\frac{D}{p^* L^2} + 6.4 \cdot 10^4\right)^{\frac{1}{5.34}} \cdot \sqrt{1 - exp\left(-\left(\frac{3000}{T}\right)^5\right)} \quad (7.2)$$

$$p^* = \frac{273}{T} p$$

Where E is the peak electric field in V/cm, p is pressure in Torr, diffusion length terms are in cm, f is frequency in GHz, and T is temperature in Kelvin.

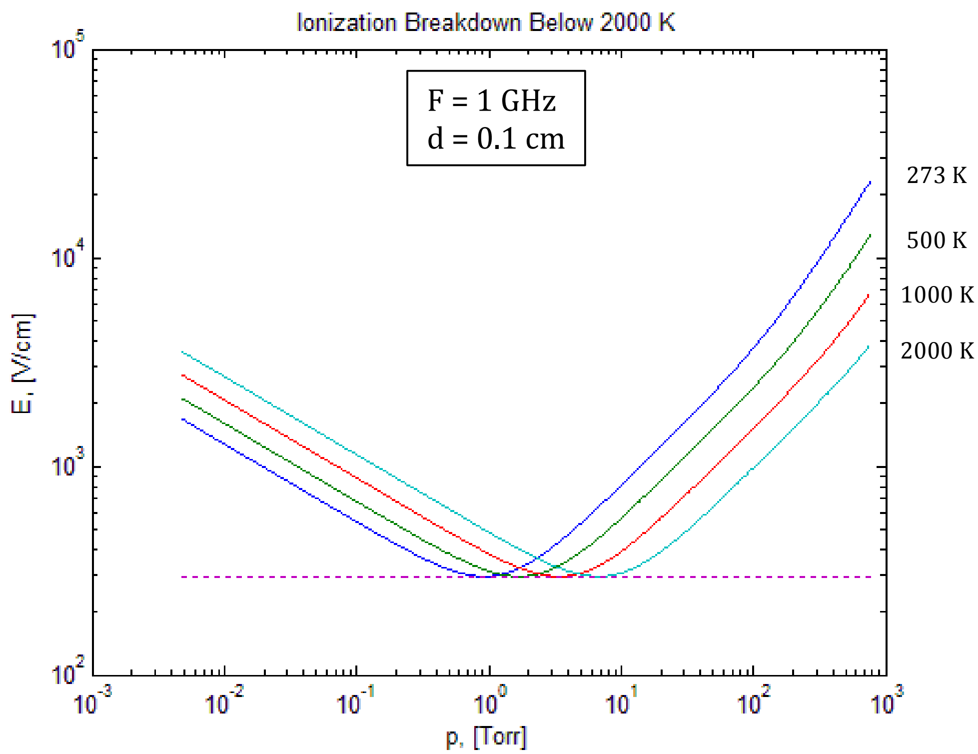


Figure 7.1. The ionization breakdown curve shifts relative to pressure over temperature ranges below 2000 K; however, the minimum breakdown does not change.

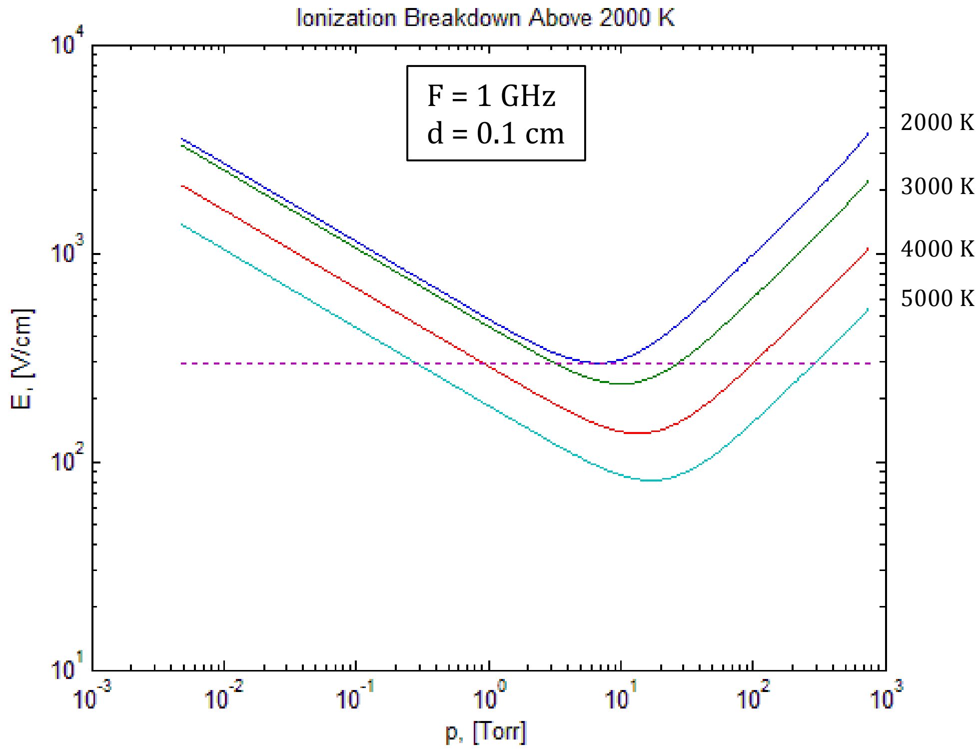


Figure 7.2. For temperatures above 2000 K, the ionization breakdown curve shifts relative to pressure and the minimum breakdown decreases as temperature increases.

8. Test Methodology

This section describes recommended test methods that can be used to meet the minimum test requirements given in section 6. The section guides the user through the diagnostic options and basic steps required to establish the ionization breakdown test bed and verify performance of the device under test (DUT). The section also outlines the general test set and instrumentation requirements used for ionization breakdown testing.

8.1 Test Equipment Considerations

Recommended ionization breakdown test setups consist of the following major functional blocks:

- **High-power RF generator:** This equipment consists of signal generators, amplifiers, multiplexers, isolators, and pulse generators. This functional block should be capable of delivering RF signals that best simulate the inputs that the device will see in normal operation. It should be capable of delivering RF power above the maximum operating power that will be seen in normal operation to demonstrate required margin. RF test set losses also need to be considered to meet delivered power test requirements at the device under test.

- **High-power RF test set:** This equipment consists of the RF input and output couplers, filters, chamber feedthrough(s), cables and/or waveguides and loads. These parts should be rated to the maximum RF generator peak and average power while having known and repeatable performance over the range of input power and frequency. Parts inside the chamber should be adequately vented and able to pass the test power levels without ionization breakdown or multipactor. Power-handling considerations apply for the test couplers operating into a shorted termination (internal loads may not be rated for full power in the reverse direction).

- **Environmental systems:** This equipment includes vacuum chamber and pump systems, bleed valves, thermal controls and measurement. These systems should be capable and verifiable to achieve the required test levels. Note intermediate pressure gauges, between ambient pressure and high vacuum, are required. Bleed valves used for fine control will require the proper gas source compatible with test requirements.

- **Global diagnostic instrumentation:** This equipment monitors the outputs of the RF test set (e.g., spectrum analyzers, RF diode detectors, and RF power meters). These devices must have known and repeatable performance over the test dynamic range and bandwidth.

- **Local diagnostic instrumentation:** This equipment consists of sensitive instruments to detect ionization within the device under test at the specific breakdown location (e.g., current probes, photon detectors).

- **Data acquisition:** This equipment consists of autonomous data sampling and recording equipment that are used for event-triggered test controls and output products for test reporting.

- **Test equipment block diagrams:** Diagrams of several main types of tests are outlined in this section. These include CW and pulsed systems followed by resonant-ring test setups.

- **DUT measurements:** S-parameter measurements should be taken on the device under test before and after the test to verify expected performance as well as no indication of damage during the test.

For CW and pulsed systems, the following diagram outlines the standard system implementation for ionization breakdown testing. This is a single source system and requires the source to deliver power levels that meet the margin test requirements in the test set.

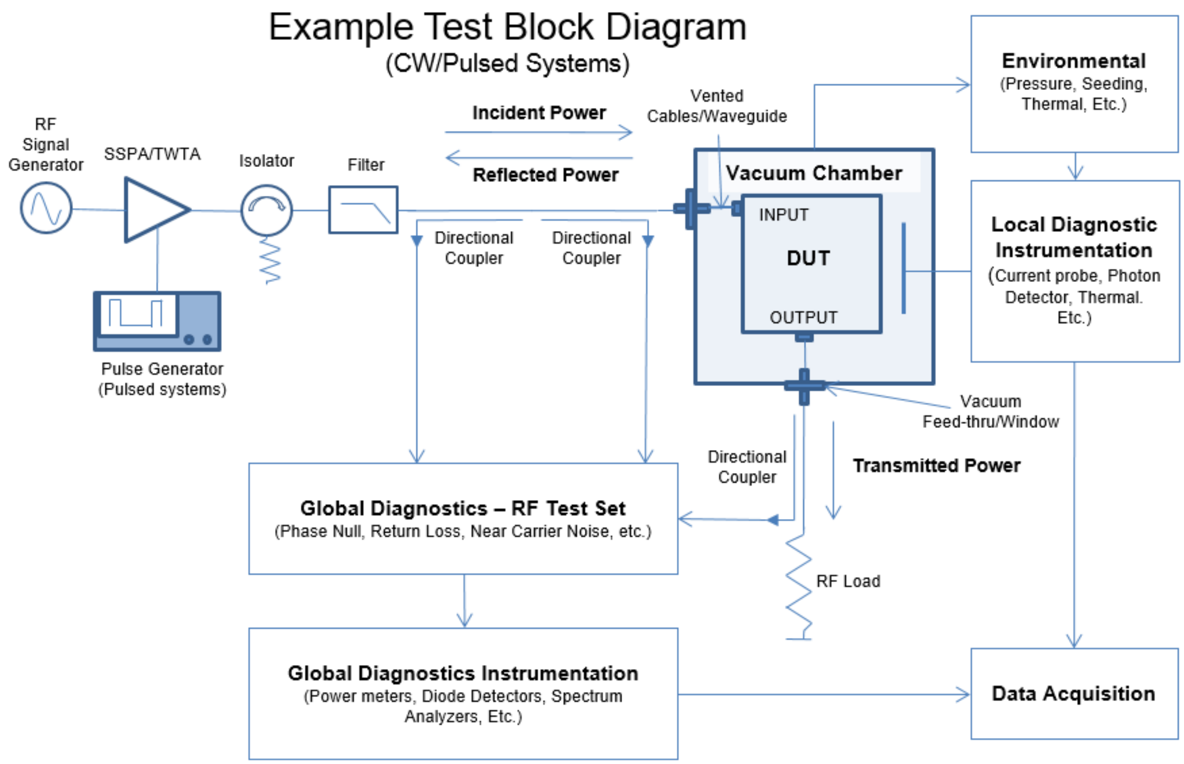


Figure 8.1. Example of an ionization breakdown test block diagram.

In order to practically provide high levels of power in excess of typical amplifier capability, a resonant ring may be used. The ring uses the resonant voltage addition within a tuned transmission line to effectively achieve the required power levels. This method is generally narrower band and specific for a single tone frequency [4] and devices with moderate insertion losses. If used, ensure that a checkout is performed for the ring critical pressure susceptibility. This is more challenging than normal setup verification as the entire ring and coupling components must be breakdown-free.

Considerations that should be addressed in the design and setup of ionization breakdown test equipment are provided below:

- **Return loss:** The input and output return loss of the test set should be better than that of the device to be tested. If the test set return loss is not better than the DUT, then additional power is required to meet the test requirements to accommodate for potential out-of-phase voltage addition resulting in lower-than-intended voltage at the device under test. In general, well-matched test equipment is available and should be used. Upstream and downstream VSWR considerations may be necessary to fully accommodate for all possible voltage additions from different sources.

- **RF power meters:** Typical RF power meters are too slow to capture fast-occurring or transient ionization breakdown events shorter than 100-500 ms. While not used for primary, high-sensitivity ionization breakdown detection, power meters provide necessary and calibrated input and output power measurements at the device.

- **Diode detectors:** Schottky diode detectors can be used for waveform monitoring and ionization breakdown detection. They have fast rise times, as well as reasonable sensitivity and dynamic range. The best rise time is achieved when operated into a low impedance such as 50 ohms, at the expense of sensitivity. Additional sensitivity can be gained by the use of a low noise amplifier to drive the diode input.

- **Isolation:** Isolation of the diagnostic instruments from the high power source is an important consideration to minimize false positives and diagnostic noise. The use of filters and isolators in the system may be needed to achieve proper isolation between test equipment and diagnostics.

- **Venting:** Test components should have sufficient venting to avoid impacting the DUT venting performance. The venting should be such that the internal pressure of any test equipment quickly reaches a value which is approximately the same as the chamber pressure. This is to ensure the setup internal pressure passes through the minimum threshold during validation.

- **Thermal:** Thermocouples are typically used to monitor unit, chamber, and test equipment temperatures. It is important to monitor the unit in multiple locations, especially where it is predicted that extremes will occur. It is important to also monitor the input test equipment where predictions indicate service temperature limits may be reached. When possible, the thermal control thermocouple should be placed on the device under test as close to the thermal interface as possible.

8.2 Test Setup Validation

The following steps should be considered in the validation of ionization breakdown test set equipment.

8.2.1 Ionization Breakdown-Free Verification

When constructing the test setup for ionization breakdown testing, the setup should be evaluated for ionization breakdown-free operation at the specific test frequency and power levels. This verification should incorporate the entire test station intended for the full component test. The device under test should be replaced with a surrogate device (such as an ionization breakdown-free connector) to join the test cables/waveguides with minimal impact on the overall RF parameters of the system. This test system should be tested through the same pressure range, at the same frequency, and to at least the maximum test power. It is recommended to validate the setup to a power higher than the test requirement to ensure that the setup has margin to the DUT power level. All diagnostics should be monitored for RF breakdown evidence with the same parameters as the component test. This test is determined to be successful with the detection of no RF breakdown events after applicable soak times at each power level. This validation does not necessarily need to be performed before each component test, but it is good practice to repeat periodically, as system components (e.g., cables and connectors) can change between DUT installations or other system alterations. If a failure is observed during test, re-running the test setup verification as part of the troubleshooting process is recommended, after consent to break configuration is granted.

8.2.2 Ability to Detect Ionization Breakdown

As required in section 6.3, a known ionization breakdown or multipactor device should be tested in the identical system as the component test. The RF power should be incremented until breakdown is detected by all detection methods to verify the successful and simultaneous operation of all detection methods. Power should be turned off immediately after detection of an event via all detection methods to prevent system contamination or damage. Although less sensitive detection methods may require higher power to

demonstrate detection, care should be taken not to damage the system due to a non-responsive detection method.

The known breakdown test should be performed at the same frequency as the device under test. Any breakdown power level can be used. The known breakdown device should have accessible internal geometries or open structures for local diagnostic method verification if that is also used on the DUT.

This known ionization breakdown device test is performed before and after the actual unit test to demonstrate no change in detection capability for the duration of the test.

Given that most detection methods behave in a similar fashion for multipactor and ionization breakdown, a known multipactor breakdown device may be used for event detection demonstration. This has the advantage of avoiding the damaging effects of ionization breakdown, assuming the device is properly vented and the demonstration is performed at less than 10^{-4} Torr. An example known multipactor device is located in the companion document, TOR-2014-02198, Appendix C.

8.2.3 Test Setup Validation Post-Failure

If a failure is noted during test, it is important to validate that the test setup has not been damaged. The first step is to inspect all hardware inside and outside the chamber for debris and damage. Inspect the chamber walls for contamination. If anything is found, clean and/or replace any damaged or dirtied components. Next, repeat the test from section 8.2.1 to ensure the setup is breakdown free. Finally, if an automatic shutoff circuit was used yet damage was still found, validate its performance.

8.3 Ionization Breakdown Diagnostic Methods

There are two types of ionization breakdown test diagnostics. The first is a local diagnostic. A local diagnostic can provide indication of ionization breakdown in a specific location if the collector is placed sufficiently close to the breakdown region. The second is a global diagnostic. This type can detect that ionization breakdown is occurring somewhere in the device, but it cannot generally pinpoint the location of the breakdown within the component. Additional information on both local and global diagnostics can be found in [5] and [6]. Most ionization breakdown detection methods will also detect multipactor with similar advantages and disadvantages.

8.3.1 Local Diagnostics

Table 8.1. Local Diagnostic Methods

Method	Effectiveness	Sensitivity	Advantages	Disadvantages	When to Use
Current Probe	High	High	Reliable, simple, inexpensive	Requires placement within vicinity of ionization region	Vented or open geometries
Photon Detector	Medium	High	Non-perturbative	Requires line of sight, sufficient neutral collisions for detection	Open geometries which are unsuitable for current probe

8.3.1.1 Current Probe

In the majority of cases where it can be applied, the most sensitive diagnostic to detect ionization breakdown is a simple current probe. This diagnostic has the added advantage of being straightforward to

implement and robust over a wide range of operating power and frequency. It also has a strong advantage in clear interpretation as ionization breakdown current is directly sampled.

Probe placement depends upon the geometry tested. The position of the probe is more important than in a multipactor test because the plasma occurs only in a localized region and can't be detected further away due to the presence of gas molecules. Additionally, once the plasma forms, it may move away from the initiation site. In a component with limited access to internal geometries, vent holes can be used to access ionization susceptible regions. In some cases, it may be necessary or beneficial to add additional or specific vent holes to accommodate this local diagnostic. The probe can be inserted into the vent hole with minimal penetration into the DUT. Care should be taken to minimize impact to the RF fields by the probe itself, noting corners and points increase susceptibility to ionization breakdown. Also verify the coupled RF in the probe does not impact the test equipment.

A metallic collector or current probe placed in the vicinity of the DUT is biased with a positive DC voltage relative to the input of a current measuring circuit, such as a picoammeter. Voltage needs to be positive relative to chassis ground. Bias is generally implemented by use of a simple battery in series with the probe collector and the input to the picoammeter. In cases with an open geometry, a larger probe area can be connected to the probe electrical connection to allow for a larger collection area. If current probes are implemented in vent hole geometries, semi-rigid cables can be used to match the vent hole size and wall thickness in order to control the overall probe penetration into the unit. In some cases, multiple current probes with known collection areas can be used to determine the local region of breakdown if multiple geometries are suspected. RF breakdown is said to occur when electron current can be measured clearly above the noise floor.

It is generally recommended to perform a "touch-test" on each current probe in which the probe tip is physically touched briefly to provide electron current to the setup. This can be used to verify connections and data acquisition.

8.3.1.2 Photon Detector

Ionization of molecules will lead to localized photon emission that can be detected either with an optical probe or intensified charge-coupled device.

The use of a photon detector requires optical access to the breakdown site. Detection is contingent upon sufficient photon counts to be measured by the detector.

8.3.2 Global Diagnostics

Table 8.2. Global Diagnostic Methods

Method	Effectiveness	Sensitivity	Advantages	Disadvantages	When to Use
Phase null	High	High	Reliable and most sensitive global diagnostic.	Quality factor (Q) of device affects sensitivity. Requires retuning during test.	Well matched devices and single tone.
Transmitted/ reflected power (high-speed)	Medium	Medium	Low-cost components via Schottky diodes. Slightly more sensitive than third harmonic.	Requires separate high-speed oscilloscope.	All situations.
Third Harmonic	Medium	Medium	Fast, reliable. Can be used for multicarrier.	Noise can be generated by other sources. Filtering can lower sensitivity.	All instances, but not combined with near carrier noise.
Near Carrier Noise	Low	Medium	Suitable for single and multicarrier systems.	Noise can be generated by other effects. Custom filtering required.	All instances, but not combined with third harmonic.

8.3.2.1 Phase Null

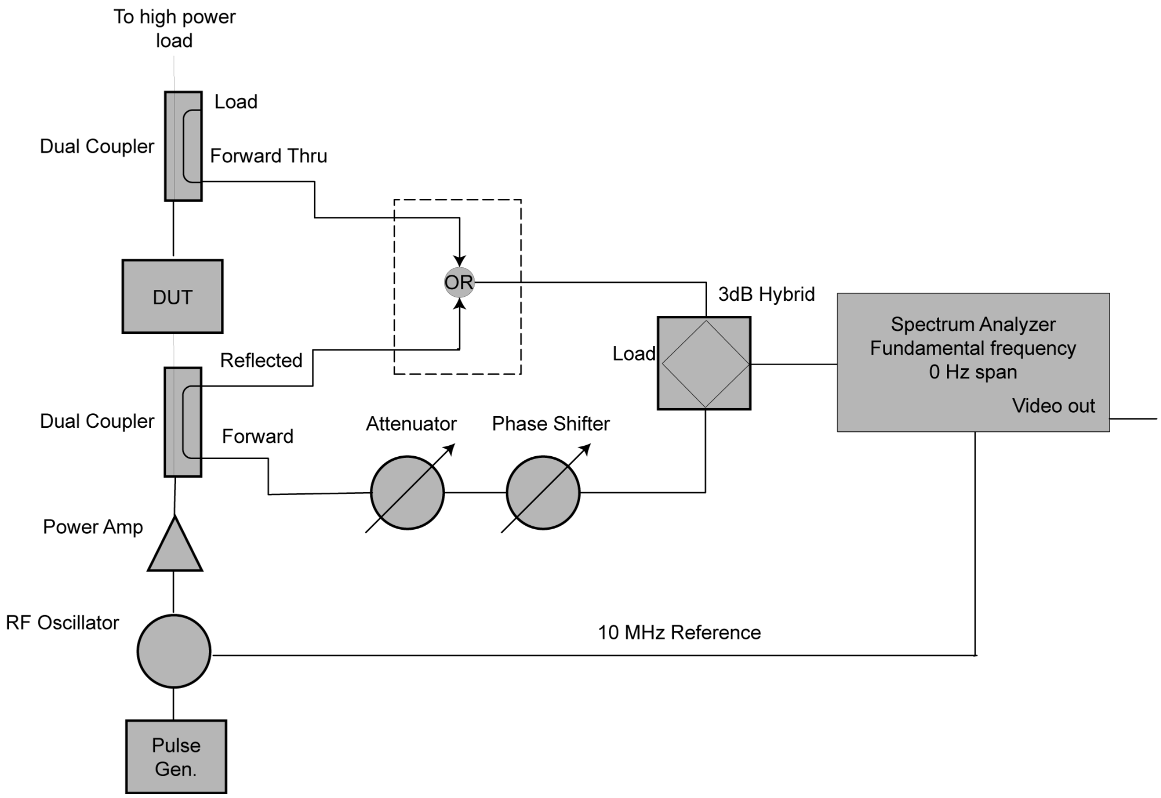


Figure 8.2. Example block diagram for a phase null diagnostic.

A conventional phase null system (Figure 8.2) uses coupled RF signal from the test setup to monitor for global changes in relative amplitude or phase changes between two RF signals, such as forward and reflected power. The presence of a multipactor or plasma discharge can change the local impedance in the discharge location, leading to near instantaneous changes in the phase and/or amplitude of either the reflected RF signal or through RF signal (measured downstream of the device under test).

As shown in Figure 8.2, the output of the combining hybrid to create the signal "null" is commonly monitored by a spectrum analyzer set to 0 Hz span at the center, fundamental frequency. Additional variable attenuators and phase shifters can be added as desired. A video out option is often used to monitor the signal level in real-time and record the analog data stream with a digital data acquisition system. Care should be taken that the analog out provides continuous sampling. If a spectrum analyzer is used, it is critical to monitor the signal in 0 Hz span, as transient ionization breakdown events can be missed if the spectrum analyzer is monitoring off the main carrier at the time of the breakdown.

One disadvantage of the conventional phase null system is that it requires manual tuning to maintain the low signal levels for sensitivity. Null detuning can occur with thermal or power changes, both of which happen throughout a typical ionization breakdown test. To maintain low null levels for best sensitivity, the test operator is required to constantly tune the attenuator and phase shifter to account for these variations. Null responses to RF breakdown can typically be discriminated from thermal or power changes based on much faster rise time and overall amplitude in the change of the phase null signal from a breakdown event.

8.3.2.2 Near-Carrier Noise

Ionization breakdown is known to produce noise near the carrier frequency. Using a spectrum analyzer, low-noise amplifier, and special notch filtering, the carrier frequency can be filtered out and the noise floor of a nearby band monitored. Breakdown will be associated with a rise in near-band signal above this noise floor. The detection of near-carrier noise is typically fast, making it well suited for either single carrier or multicarrier detection. Care must be taken with pulsed discharges such that harmonics are not generated in the measurement band. In addition, it can be difficult to ensure that observed noise is due to breakdown and not due to other effects from the test setup, such as loose connectors. [6] Additionally, care must be taken to ensure that the detection frequencies are within the passband of the test device.

Care should be taken when using near-carrier noise concurrently with third harmonic detection as the only two global diagnostics because the same non-breakdown events can cause false readings in both detection methods, possibly creating a condition for a false negative test result.

8.3.2.3 Third Harmonic

During ionization breakdown, noise is not only generated at the carrier frequency but also at harmonics of the carrier frequency. Detected increase in harmonics of the carrier frequency is a common diagnostic for RF breakdown. While other harmonics may be considered, the third harmonic is typically most sensitive and widely used. A filter for the high-power input signal is typically required to reduce harmonic noise from the amplifier(s) and maintain a sufficiently low signal-to-noise ratio for harmonic detection as a breakdown diagnostic.

Implementation of the third harmonic diagnostic is similar to that for near-carrier noise, with different system filtering. Third harmonic detection is often fast and readily accessible through common RF coupled ports. It can be used in both single and multicarrier systems. Care must be taken to filter out harmonic noise products from the amplifier as well as any passive intermodulation products that could be generated within the system. Like the phase null, the third harmonic signal is typically monitored on a spectrum analyzer set to 0 Hz span (same rationale as phase null). The spectrum analyzer output is then monitored via video/analog out that can be monitored with other high-sensitivity diagnostics.

As mentioned in section 8.3.2.2, care should be taken when using near-carrier noise concurrently with third harmonic, as a non-breakdown distortion generating event can cause false readings in both detection methods, possibly creating a condition for a false negative test result.

8.3.2.4 Transmitted/Reflected Power

Using available RF coupled ports, transmitted and reflected power signals can be monitored via Schottky diodes/crystal detectors. As analog measurement devices, these diodes can monitor fast changes in transmitted and reflected signals that can correlate with a plasma discharge. The analog DC output of these detectors can typically be monitored by the same data acquisition system as other high-sensitivity diagnostics. Commonly, RF transmitted power through the DUT may drop, while the RF reflected power may increase in the presence of a plasma. Specific amplitude changes will depend on the plasma size and density. Another option is to monitor transmitted or reflected RF field directly (2*frequency) with a sufficiently fast data sampling system or scope.

8.4 RF Breakdown Observations

Other observations may occur with initiation of RF breakdown. The following observables can be used for correlation to RF breakdown, but they are often insufficient and unreliable for high-sensitivity and

real-time detection. If these are observed during test without indication on the primary diagnostic methods, this may indicate a failure and further investigation is warranted.

8.4.1 DUT Temperature Increase

Ionization breakdown can cause localized heating of the device in the breakdown region. Timescales for temperature rise observables are large compared to high-sensitivity diagnostics, and they will depend on the thermal time constants of the DUT. In many cases, thermal detection via external-mounted thermocouples on the DUT is far too slow to prevent internal damage.

8.4.2 Direct Plasma Observation

In the event of open or visually-accessible geometries, ionization breakdown can be observed optically via localized glow discharge of the plasma (corona) while RF power is being applied.

8.4.3 RF Performance Changes

If a breakdown occurs and damages the part, it is possible that the RF performance, such as S-parameters, may change as a result. It is recommended to measure S-parameters before and after the test.

8.4.4 Changes to Hardware

Local heating during ionization breakdown may be sufficient to damage (melt) device features, creating visually observable damage as well as performance changes.

Additionally, post-test observation of localized changes to the device walls can be seen in some cases. Discoloration is commonly due to dielectric carbonization and deposition onto metallic walls by means of the plasma discharge. Such discoloration can provide evidence of the location of the plasma breakdown.

8.5 RF Shut-Down Protection System

Ionization breakdown can cause significant local heating leading to internal melting, deposition, carbonization, and other damaging situations. Use of an RF shutdown protection system [7] should be incorporated to lower the probability of device damage. The system should be designed to turn off the high-power RF signal if a predefined threshold is exceeded. Response time should be as fast as practical to prevent damage to the DUT.

Shutdown systems should be triggered by the most sensitive and reliable diagnostic in the test configuration. Multiple diagnostics can be incorporated into the shutdown logic when possible.

8.6 Pressure Operation

For successful verification of RF breakdown handling, the DUT should be transitioned through the pressure requirement at a controlled rate. The following considerations should be addressed.

8.6.1 Pressure Profile

For DUTs being verified for launch conditions or other time-varying pressure profiles, the pressure transition rate should be slower than the DUT will experience in operation to provide sufficient time to detect breakdown at the worst-case condition. For DUTs being verified for a fixed pressure (e.g., high-altitude platform, Mars lander) the chamber should be held at the worst-case pressure for the duration of the test as described in section 8.9.1. Note that the internal DUT pressure will lag the chamber pressure.

Also note that most pressure gauges have a known uncertainty that should be considered when determining the pressure range of the chamber during testing.

The composition of the gas present in the test should be specified. The most common is local air. Alternate requirements would be dry nitrogen, dry air, or a composition determined by the environment where the DUT will be in service. Dry nitrogen is generally the worst-case gas to use if the operational environment is air.

Verify the pressure gauge measures the specified gas accurately. There may be a calibration curve defined for the particular composition.

After sufficient time for the DUT internal pressure to transition through critical pressure, bring the chamber pressure to less than 10^{-4} Torr, or to the final high pressure if testing upwards, and soak with power applied. Testing this way will minimize the chance that there is a circuitous vent path keeping the pressure above (or below) critical pressure.

8.6.2 Flow Control

Chamber pressure is usually decreased from atmospheric to low vacuum pressure levels by using a roughing pump. The rate of decrease must be controlled by a separate valve placed either between the roughing pump and the chamber or as a bleed into the chamber. Although it may be the most efficient method, the installation of a bleed valve between the roughing pump and chamber may be impractical. In order to satisfy the gas composition requirement, it may be necessary to evacuate the chamber and backfill with the required composition prior to start of testing. If the bleeder valve is not in line with the roughing pump, then it will require a connection to the specified composition of gas.

8.6.3 Sample Ascent Profile

A sample ascent profile is shown in Figure 8.3. This is from the Delta IV Launch Services User's Guide. [8] This is not a worst-case bounding profile, but merely an example. The ascent profile of the particular mission of the device should be used to help determine the necessary test pressure profile. It is very difficult to recreate and exact pressure profile with a vacuum chamber; instead, it is recommended to stop and soak at discrete pressures to effectively recreate the profile with margin. Note that the launch profile is different from the typical pressure profile provided by thermal vacuum test chambers.

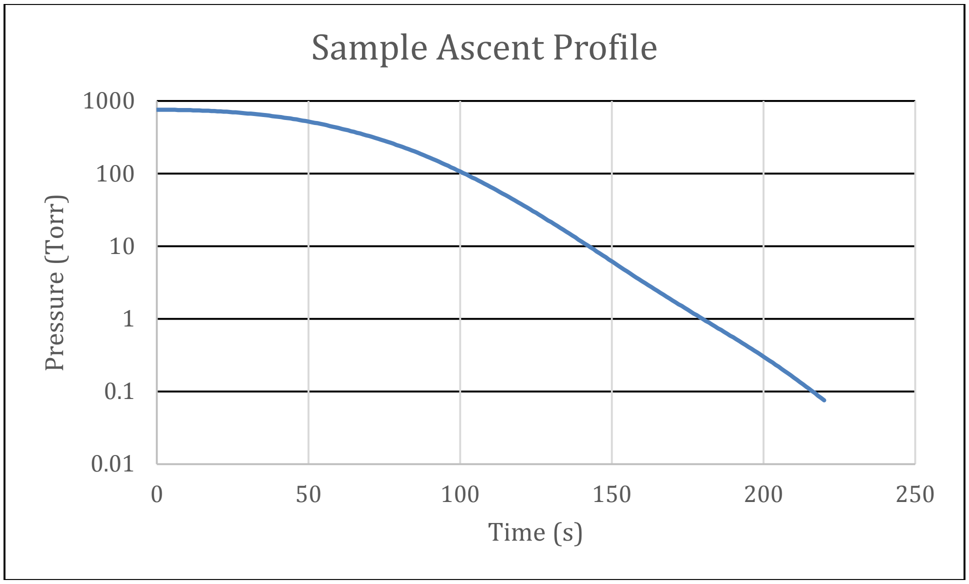


Figure 8.3. Example launch ascent pressure profile. [8]

8.7 RF Test Operation

For successful verification of RF power handling, the DUT should be exposed to the maximum peak power requirement including margin. If the signal is pulsed or there is concern with over-testing the average power handling of the DUT, a pulsed signal should be used for test. Selecting a narrow pulse width may be advantageous to minimize damage in the case of a failure.

The most common concern for ionization breakdown is during launch. For this case, the RF power at the DUT should be increased to the desired test level at ambient pressure at a rate that prevents thermal stress. The DUT should be thermally stable prior to start of the pressure profile. Constant pressure testing is discussed in section 8.9.1.

It is recommended to perform the ionization breakdown verification testing as late in the test sequence as possible, after all environmental tests such as random vibration and thermal cycling have been completed. It may be permissible to perform ionization testing and multipactor testing in sequence using the same test system.

8.8 Data Acquisition and Reporting

8.8.1 Data Recording

As mandatory data items, the outputs of the ionization breakdown detection methods, power meters, pressure, and temperatures should be recorded continuously. If spectrum analyzers are used, the continuous analog output proportional to the measured signal should be recorded. This is typically through a “video out” output connector. Note that some modern spectrum analyzers digitize the data and thus are not actually true analog outputs. The screen “maximum hold” feature alone is not sufficient data collection due to insufficient resolution and video bandwidths that can lead to missing data and incomplete breakdown detection.

8.8.2 Sampling Rates

Sampling rates for data recording vary amongst test equipment. The detection methods should be fast enough to capture events at the threshold of sensitivity for that particular method. This depends on the pulse width. The sampling rate should be fast enough to capture an event on any pulse. For example, a 500 microsecond pulse width requires a 4 kHz sampling rate in order to ensure that every pulse has at least 2 data points. To capture the entire envelope and transitions with optimal resolution, an even higher sample rate is advised.

For CW testing, the sample rate should be high enough to capture the envelope or duration of the breakdown event.

For other equipment, such as power meters, thermocouples, or pressure gauges, sampling can occur at a much slower rate. A typical sampling rate for a power meter or thermocouple is 1 Hz.

For situations in which large and difficult-to-manage data files are produced, triggered data storage may be implemented for the faster data rates, though continuous monitoring of the maximum possible signals for all diagnostics should be maintained.

8.8.3 Minimum Data Items

- Continuous data recording of all detection methods, power meters, pressure, and thermocouples

- Evidence from each of the detection methods showing the breakdown of the known breakdown device

- Evidence that temperatures and pressures were within specification limits during the test and that all dwell times were met

- If any events were recorded on the DUT, there should be images of the events on the detection methods and detailed descriptions of the test conditions during the event(s)

8.8.4 Test Report Guidelines

A test report shall be of typical scientific or laboratory format. At a minimum, the following sections should be included:

- Executive summary
- Purpose
- Reference documents
- Unit description
- Test description
- Test setup
- Setup verification
- Known breakdown pre-test
- Ionization breakdown test details
- Known breakdown post-test
- Conclusions

8.9 Alternative Test Methods

8.9.1 Constant Pressure Test

If a hermetic device does not meet analytical margin requirements, or if a device will be operating in an intermediate pressure environment, it may be necessary to demonstrate that the device can operate without breakdown at constant pressure. This is different than the swept-pressure type of test described in other parts of the document.

Backfill the chamber with the gas in which the unit will operate. Verify the pressure gauge measures the specified gas accurately. There may be a calibration curve defined for the particular composition.

The power should be applied in steps starting about 10 dB below the nominal operating power. Prior to the first step, the power should be set at a level to verify instrumentation is responding normally, but below a level that will cause breakdown. The minimum soak time at each power level should be at least five minutes and include sufficient time for the DUT to stabilize thermally.

Thermal cycling should be considered where the DUT will operate at power over a range of temperatures as this can change gaps inside a unit due to differences in material coefficient of thermal expansion. Cycling is performed after bringing the DUT to full power at ambient temperature. There should be a soak at the temperature extremes that includes a thermal stabilization requirement.

To perform this type of test, follow these steps:

1. Ensure the unit internal pressure can equalize quickly to the chamber pressure.
    a. For a flight device, the design should include sufficient vent holes. For a hermetic device, this can be performed before final seal or on a non-flight device with venting added.
2. Install device in chamber.
3. Apply required test power level to unit at starting pressure.
4. Slowly reduce (or increase) pressure to required intermediate level using the roughing pump and leak valve.
5. Arrive at final required pressure level. Depending on flight application and venting, dwell at this pressure for amount of time needed to validate performance at this pressure.

8.9.2 Threshold Test

In some cases, such as on an engineering development unit or in a failure investigation, it is desirable to determine breakdown threshold by testing. This can be a destructive test, but important information can be learned. Because there will be repeated breakdowns, it is recommended to use a narrow pulse width and electron seeding.

To perform this type of test, follow these steps:

1. Estimate the critical pressure (Torr) for the unit based on frequency. For a unit with unknown gaps, it can be approximated by 0.8 times the frequency in GHz.

2. Bring chamber to pressure slightly above estimated critical pressure. Typically, 1–2 Torr higher is preferred. If the unit is not well vented, dwell at this pressure until the unit has reached the desired pressure. Alternatively, as this is a non-flight unit, add venting features.

3. Keeping chamber pressure constant, apply power in increasing steps with short dwell times (about five minutes) until breakdown is noted. Turn off power immediately to prevent damage. An automated shut-off system is recommended. Repressurize system to atmospheric pressure.

4. Decrease pressure to slightly below estimated critical pressure.

5. Keeping chamber pressure constant, apply power in increasing steps with short dwell times (about five minutes) until breakdown is noted. Turn off power immediately to prevent damage. An automated shut-off system is recommended. Repressurize system to atmospheric pressure.

6. Based on data received from first two pressures, set chamber to a new pressure that is estimated to have a lower breakdown threshold. Repeat steps 2–5 with new pressures until the critical pressure is found. Plot data in a curve such as the one in Figure 8.4.

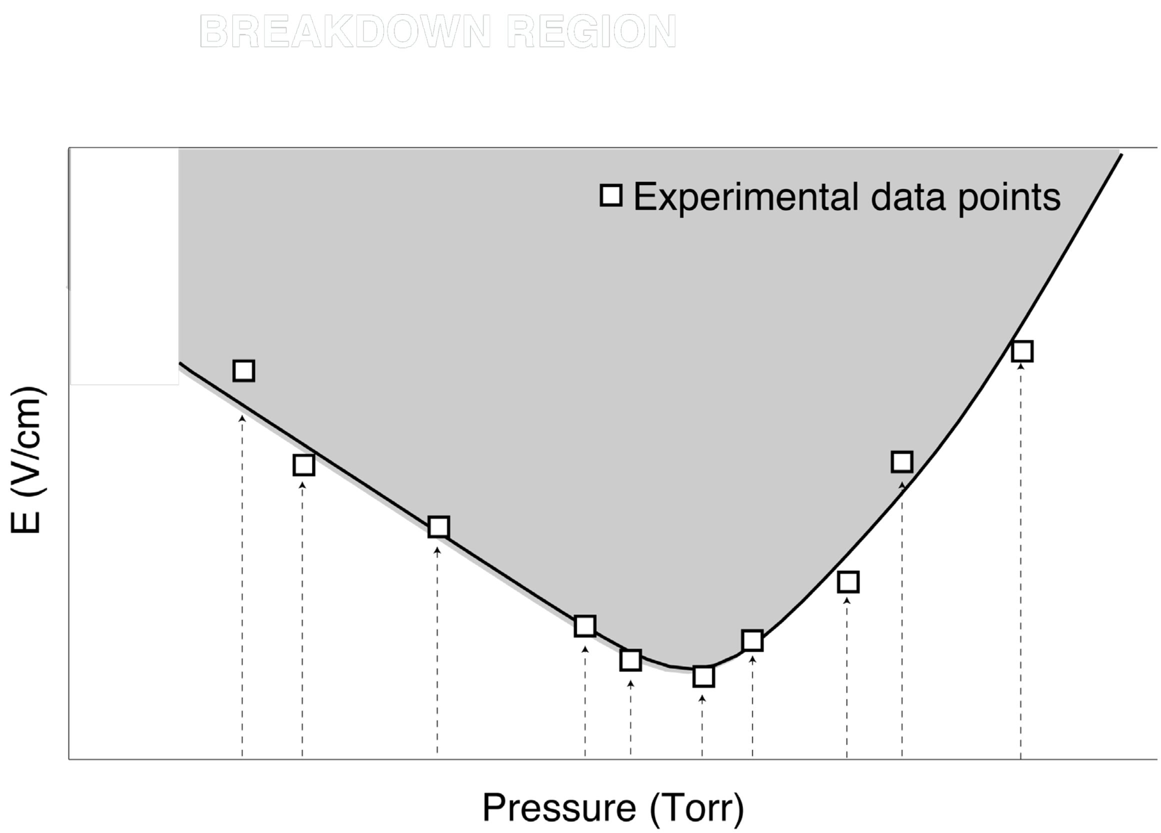


Figure 8.4. Example test threshold curve.

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Appendix A. Hermetic Devices

A.1 Introduction

In cases where it is difficult to design a unit that will operate without breakdown at low pressure or at vacuum, devices can be made hermetic. This approach can mitigate both multipactor and ionization breakdown risk or be used for other reasons, such as preventing moisture absorption when in ground storage. For the purposes of this document, a hermetic component is a device that is sealed against external gas or fluid pressure. Typically, the device is filled and sealed such that the internal gas density is higher than its nominal operating environment, usually one atmosphere at the beginning of life with a low leak rate.

Generally, for most applications of this ionization breakdown document, the minimum electric field required to break down the device is the only number of concern (at the critical pressure). For hermetic devices, the shape of the curve is also important. Verification of both the RF breakdown susceptibility of the component design and the hermeticity (leak rate) of the component are required to determine the minimum breakdown conditions. If ionization breakdown analysis is not available, testing a vented version of the device at its minimum internal pressure at the maximum power level with margin is acceptable for acceptance or engineering level testing.

This section provides a common, simple approach for hermetic hardware. More refined approaches are available but not in the scope of this guiding appendix.

A.2 System Considerations

General system considerations for verification of a hermetic component are the same as for a non-hermetic component. The frequency determination and worst-case power level are the same as outlined in section 3.

The additional parameters that must be considered for a hermetic unit are internal volume, mission life, and detectable leak rate. Based on the mission life requirement and the unit gas volume, a worst-case leak rate for the hermetic seal should be defined and a desired component lifespan determined. To be acceptable, the final internal pressure at end of mission life must be above the ionization breakdown threshold plus margin.

Note that interfaces, such as feedthrough connectors that are outside the hermetic cavity, should be analyzed for the appropriate pressure environment.

A.3 Qualification Process

Analysis should first be performed on end-of-life pressure as well as ionization breakdown margin. The hermetic seal of the units cannot be qualified by analysis. All units should be tested for gas leak rate during manufacturing and acceptance test.

A.4 Margin

In a hermetic device, it is over-conservative to calculate margin to the minimum of the Paschen curve. Instead, margin is calculated relative to the breakdown threshold at the end-of-life pressure inside the unit. Because of this, there are different analytical margins levied than in other sections.

IB breakdown analysis margin should be applied the same way as in sections 5 and 7. The only difference is that the IB breakdown threshold level is levied at the final pressure, not at the critical pressure.

For final pressure, as appropriate, add margin to mission duration to ensure that final pressure will be as predicted by leak rate. Margin applied should be consistent with risk profile of the mission as well as uncertainty in the leak rate analysis.

A.5 Analysis

Unlike a standard analysis that validates performance to the lowest power on the breakdown curve, a hermetic device requires analysis to a higher pressure on the curve. This is the intermediate pressure which the unit is expected to have at the end of life from low-level leaking.

Two types of analysis should be performed on a hermetic device. Either analysis can be performed first. Either the maximum leak rate can be calculated from the final pressure needed to pass breakdown analysis per section 5 or the allowable final pressure can be calculated from the detectable leak rate.

Note that devices which are pressurized with nitrogen should not be verified using the breakdown curves for air given in section 5.2. Breakdown thresholds for nitrogen tend to be comparable at the minimum but are substantially lower than the air threshold at higher pressures.

A.5.1 End-of-Life Pressure

To calculate the end-of-life pressure, follow these steps. These equations are for pressurization at one standard atmosphere of pressure. Adjustments should be made for other pressurizations.

1. Determine unit internal gas volume. Ensure that any solid structures inside the hermetic box are subtracted from the volume.

2. Obtain desired mission life time.

3. If no leak is measured, use the minimum detectable leak of the equipment. If there is a measured leak, use that leak rate.

4. Determine initial pressure of gas inside unit when sealed at standard temperature.

5. Calculate the final pressure after mission life with either of the following formulas:

$$R_L = -V\frac{dP}{dt} \tag{A.1}$$

$$P(t) = P_0 e^{-\left(\frac{R_L t}{V}\right)} \tag{A.2}$$

where $P(t)$ is pressure as a function of time, P_0 is initial pressure, V is gas volume of unit, t is the required life time, and R_L is the measurable threshold of the available leak rate detection method.

A.5.2 Ionization Breakdown Margin

To determine the allowable operating power at the end-of-life pressure, follow these steps.

1. Follow the analysis process in section 5 for the appropriate category for the device.
2. Determine the breakdown threshold at the end-of-life pressure.

3. Add power margin required per Table 4.1 at the final pressure determined in step 2.
4. Compare result to required operating power.

The unit should pass this analysis to be used on a mission.

A.6 Test

A.6.1 Device That Passes IB Analysis

All hermetic units should be tested during manufacture to validate the leak rate. It is recommended that testing occur after initial build as well as after each environmental test.

There are many kinds of leak tests. Typically, a unit is pressurized with some fraction of helium gas for use in leak detection. A helium leak test is then performed on the entire unit. If the amount of helium is not known prior to the test, a helium bombing test can be performed. Helium bombing is a process in which a pressure vessel is filled with helium to a high pressure in order to introduce a known quantity of helium.

Details of how to perform leak testing are not included in this document.

A.6.2 Alternative Qualification Test

For a hermetic cavity containing category 3 device(s), or if the leak rate cannot be proven to meet life requirements, an alternative test can be performed that will qualify the unit. The test method for RF breakdown requires testing a component at the minimum expected pressure (or critical pressure if the minimum pressure is below the critical pressure) at which it will operate. This test can be done on the flight unit before the hermetic seal is complete or with an engineering unit with a vent hole that allows it to track with chamber pressure. The test should be performed at worst-case test power (see section 3) at constant pressure equivalent to the end-of-life pressure from the analysis section. Refer to section 8.9.1.

Appendix B. Background

Ionization breakdown in a gas is defined as the process by which number of charged particles grows exponentially within a short time to considerable plasma density. The energy for charge multiplication comes from an externally imposed electric field. The field could be either stationary (DC) or alternating (AC). The focus of this appendix is ionization breakdown in AC electric field in a frequency range greater than 100 MHz, which for the purposes of this document will be called the RF frequency range.

Small numbers of stray electrons, mainly from random ionization events produced by cosmic rays, always exist within a volume of gas. When an applied electric field amplitude is strong enough and the collision rate between electrons and neutral gas particles is low enough, electrons may be accelerated to the energies sufficient to ionize gas molecules upon impact (impact ionization). An electron avalanche may quickly develop when a single electron can undergo multiple ionization collisions before leaving the volume of gas (either by colliding with the wall or diffusing out of the breakdown susceptible region).

Fundamental analysis of the RF breakdown is complicated by the fact that the electric field is not steady on the time scale comparable with the electron motion. While multiple attempts have been made to apply first principles to the RF breakdown analysis [9] [10], the most successful theories remain semi-empirical. The standard approach is to write down the rate equation for production of plasma in a volume of gas, known as the equation of mass continuity for charged species. While other gases, such as helium, may be easier to analyze, breakdown in air is the most relevant for practical applications. For air, the mass continuity equation can be written as: [11]

$$\frac{\partial n}{\partial t} = Sources - Sinks = \nu_i n + [\nabla \cdot (\mathrm{D}\nabla \mathrm{n}) - \nu_\mathrm{a} n] \tag{B.1}$$

where $n, \nu_i, \nu_a,$ and D are plasma density, ionization and attachment frequencies, and diffusion coefficient, respectively. For air, other rate coefficients, such as electron recombination, have been shown to be small compared to the ionization and attachment. [11] The solution to Eq. (B.1) requires prior knowledge of the ionization and attachment rates as well as the diffusion coefficient. The rates have been measured to be a function of the electric field, pressure, and temperature, while the diffusion coefficient was shown to depend on position, pressure, and electric field, as shown in Figure B.1. [12] [13]

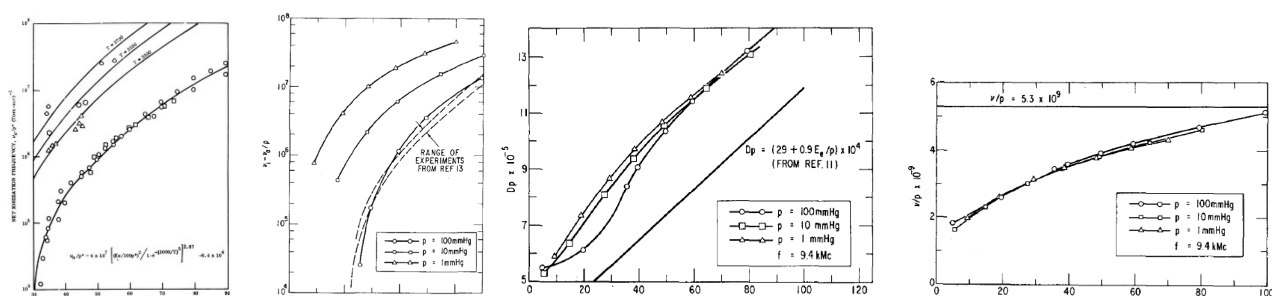


Figure B.1. Effective ionization rate, panel (a) and (b); diffusion coefficient, panel (c); and collision rate, panel (d). Effective ionization rate has been shown experimentally to be a function of temperature, pressure, and electric field. Diffusion coefficient and collision rate were shown to be a function of electric field and pressure. [10] [12]

In that figure, the first two panels show the effective ionization rate, $\nu_i - \nu_a$. It should also be noted that $E_e$on the x-axis refers to the effective electric field defined as

$$E_e = \frac{E_{rms}}{\sqrt{1+\left(\frac{2\pi f}{\nu_c}\right)^2}} \tag{B.2}$$

where E_{rms} is the root-mean-square electric field amplitude of the oscillating signal, f is the signal frequency in Hz, and $\nu_c$is the collision frequency of electrons with heavy species in the gas, which itself depends on electric field and pressure, as shown in the last panel of Figure B.1.

Empirical fits to the measured coefficients could be used to solve Eq. (B.1) numerically to produce results that provide a good match to available experimental data. Alternatively, with the assumption of a spatially uniform breakdown, one may simplify Eq. (B.1) to the following breakdown threshold:

$$\nu_i - \nu_a = \frac{D}{L} \tag{B.3}$$

where D is constant throughout the breakdown-susceptible region (but still dependent on E_e and p), and L is an "effective" diffusion length, which can be calculated for some simple geometries. A list of these geometries and their effective diffusion lengths are given in Table 5.3. With the empirical fits to the measured effective ionization rate [14], collision rate, and diffusion coefficient, shown in Figure B.1, Eq. (B.2) may be solved for breakdown threshold:

$$E_{peak} = 5.3p^* \sqrt{1+\left(\frac{2\pi f}{\nu_c}\right)^2} \cdot \left(\frac{D}{p^* L^2} + 6.4 \cdot 10^4\right)^{\frac{1}{5.34}} \cdot \sqrt{1 - exp\left(-\left(\frac{3000}{T}\right)^5\right)} \tag{B.4}$$

$$p^* = \frac{273}{T} p$$

where p is pressure in Torr and T is the gas temperature in Kelvin. A curve of $E_{rms}\ vs.\, p$ is called a Paschen breakdown curve. It should be noted that alternative empirical fits to the rate coefficients have also been reported. [2] [1] [15] [16] These semi-empirical fits show that temperature is an important factor in air breakdown. Under 2000 K the Paschen curve shifts to higher pressures, as shown in Figure 7.1, although the minimum breakdown threshold remains unchanged. Above 2000 K, where chemical changes in air composition become important, the breakdown threshold decreases and critical pressure increases, as shown in Figure 7.2.

A simple rule of thumb described by

$$E_{peak} = 32 \cdot \sqrt{2} \cdot \sqrt{p_{Torr} + 2f_{GHz}} \tag{B.5}$$

appears in [1] without any justification, but it provides a good match to the measured data in the attachment controlled regime of Paschen breakdown for air. This equation is plotted in the right panel of Figure B.2 and is appropriately marked.

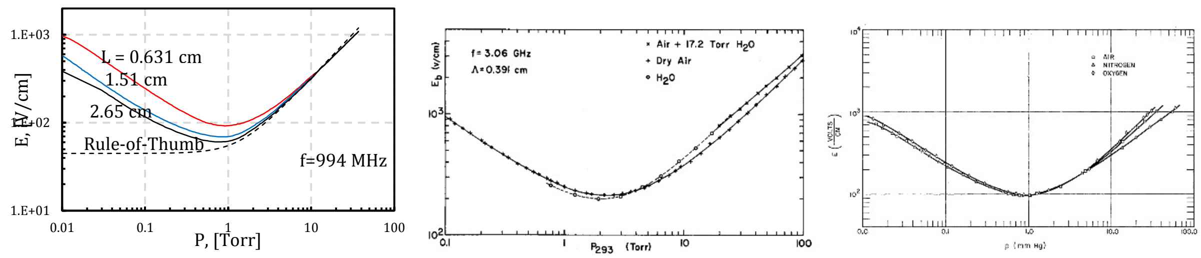


Figure B.2. Theoretical Paschen curve dependence on the effective length L is shown in left panel. Moisture dependence is shown in the middle panel and air composition dependence is shown in right panel.

The right panel in Figure B.2 also shows how Eq. (B.4) depends on the effective diffusion length L. It can be seen that the Paschen curve has two regions controlled by fundamentally different physics. In the low pressure regime, plasma losses are dominated by diffusion of electrons. In the high-pressure regime, plasma losses are dominated by attachment and are largely independent of geometry, as manifested by the convergence of the lines at high pressure (see top right panel of Figure B.2.) Equation (B.4) is in good agreement with measured Paschen curves for various geometries filled with air in the attachment controlled regime. The empirical equation also provides relatively good agreement to the data in the diffusion controlled regime for large values of L. As the effective length decreases, the agreement between data and Eq. (B.4) degrades. A wealth of empirically-measured Paschen curves for various geometries exists in the open literature [9] [17] [18], and can be compared to Eq. (B.4).

Paschen curves for various gases and mixtures can be found in the open literature; however, air is the primary focus of this document. Nevertheless, it is important to mention effects of moisture, as well as air constituents on the breakdown behavior. Moisture plays an insignificant role on the breakdown threshold at low pressure, particularly at the minimum of the curve, as can be seen from the bottom left panel of Figure B.2. At higher pressures, though, moisture may increase breakdown threshold by about 1.5 dB. Thus, performing tests in dry air should always provide margin against humid environment.

Paschen curves for air, nitrogen, and oxygen are shown in the right panel of Figure B.2. The most important conclusion from those graphs is that at the minimum of the breakdown curves the breakdown threshold is nearly identical. Away from the minimum, the nitrogen curve provides as much as 3 dB margin (at high pressure) against air.

Pulsed Breakdown

The issue of pulsed RF breakdown has been investigated by a few authors. [9] [10] [11] [2] At a low repetition rate or low duty-cycle, pulsed threshold does not significantly vary from the CW RF breakdown. However, as the off-time is shortened, the threshold tends to decrease linearly. This effect also becomes more pronounced at lower pressure. A basic explanation for these observations is that with shorter off-time, more and more charged particles remain within the volume by the time of the subsequent pulse, thus reducing necessary power to start the next discharge.

Magnetic Fields

Analysis of RF breakdown in the presence of a magnetic field is challenging, and a limited amount of work has been reported in literature on this complex topic. [19] [20] [21] Some papers report significant

breakdown threshold reduction at the resonant condition—when the driving frequency is near the electron cyclotron frequency. [19]

DC Bias

DC bias of the device may also play a significant role in the breakdown threshold. Taylor, et al. [10] discusses various issues of DC biasing in antennas, including RF breakdown mitigation.

Appendix C. Comparison of Analytical Curves and Test Data

In this appendix, Eqs (5.1) and (5.2) are compared to the Woo curves [17] for coaxial devices with frequency-gap values ranging from 20 MHz-cm to 2500 MHz-cm. Comparison to the rule-of-thumb equation [Eq. (5.1)] is provided in Figure C.1, and comparison to the semi-empirical equation [Eq. (5.2)] is provided in Figure C.2. The rule-of-thumb equation is in all cases conservative to the Woo curves. The semi-empirical equation agrees very closely with the Woo curves at high-frequency gap values, but is also conservative to the Woo curves at the Paschen minimum.

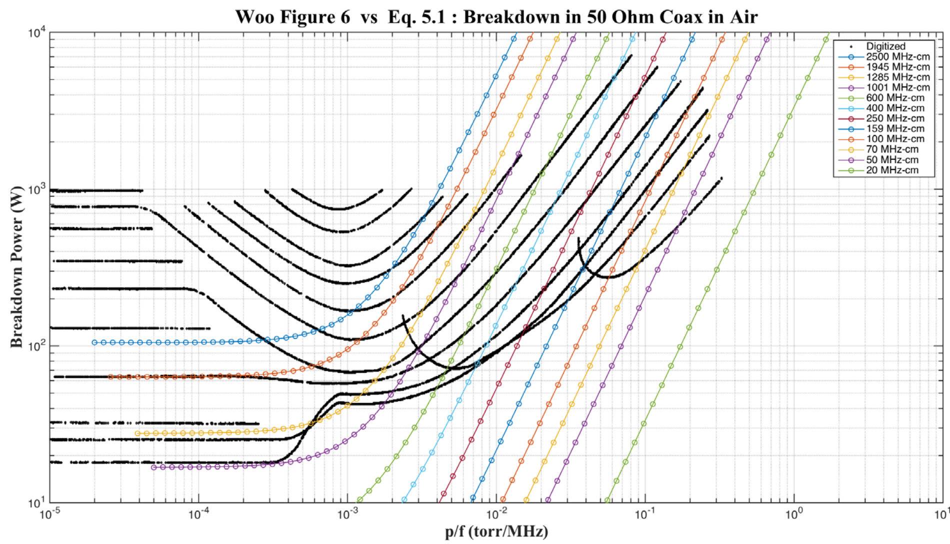


Figure C.1. Comparison between Eq. (5.1) (rule-of-thumb, solid black) and Woo curves. [17]

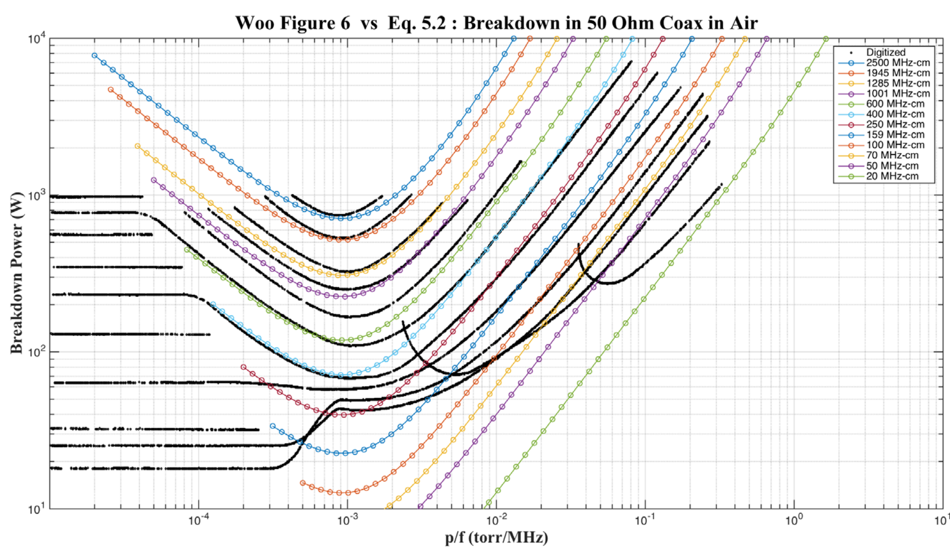


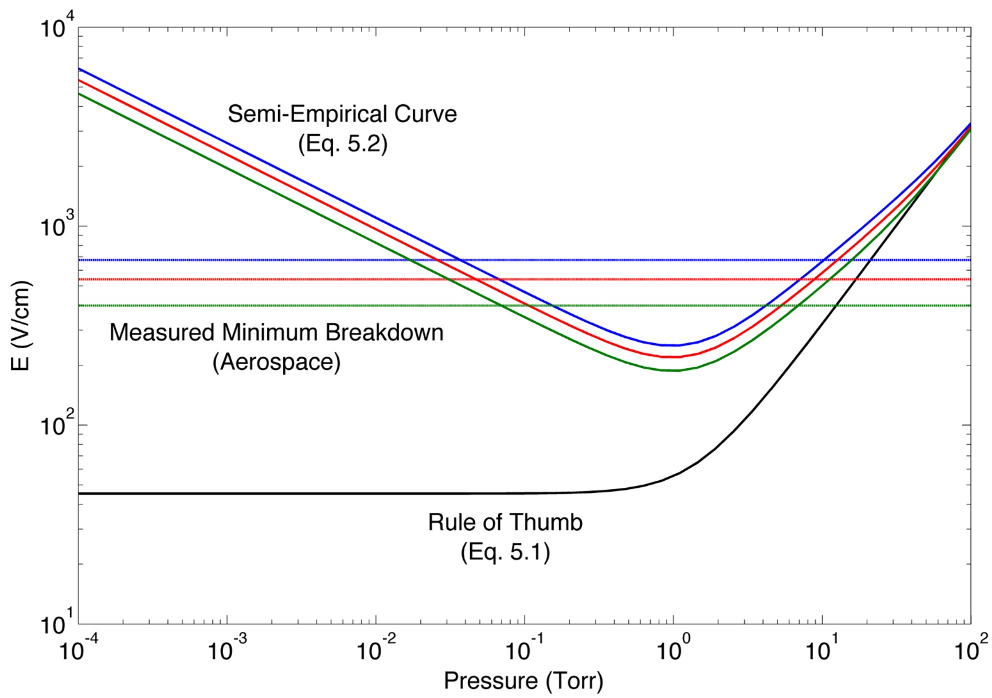
Figure C.2. Comparison between Eq. (5.2) (semi-empirical, solid black) and Woo curves. [17]

The ionization breakdown minimums for three coaxial breakdown devices are measured and compared to Eqs (5.1) and (5.2) in Figure C.3. Inner and outer diameters and effective diffusion length (Table 5.3) are

given for the three devices in Table C.1. Each device was tested for its minimum breakdown threshold at the Aerospace Multipactor Lab for air at f = 1 GHz. Breakdown was detected via current probe placed within the vicinity of the device vent hole.

Table C.1. Effective Diffusion Lengths for Example Coaxial Geometries

Gap length d (mm)	Outer radius a (mm)	Inner radius b (mm)	L_D^{-2} (m^{-2})
1.8	3.0	1.2	$3.2 \cdot 10^6$
2.6	4.6	2.0	$1.5 \cdot 10^6$
3.8	6.8	3.0	$6.8 \cdot 10^5$



d =3.8 mm
d = 2.6 mm
d = 1.8 mm

Figure C.3. Measured minimum breakdown electric field for three coaxial devices at f = 1 GHz.

The above electric fields are converted to power and plotted for one of the devices in Figure C.4 below. At critical pressure, there is 3.6 dB of margin between the measured minimum and the minimum in the Paschen curve [Eq. (5.2)]. There is 16 dB margin between the measured minimum and the minimum in the rule-of-thumb equation.

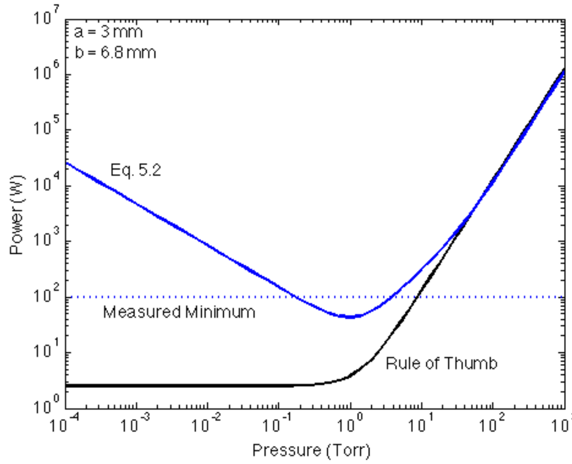


Figure C.4. Measured minimum breakdown power for a coaxial breakdown device at f = 1 GHz.

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